Technical Report REMR-CS-52
January 1997

US Army Corps of Engineers
Waterways Experiment Station

Repair, Evaluation, Maintenance, and Rehabilitation Research Program

Results of Laboratory Tests on Materials for Thin Repair of Concrete Surfaces

by W. Glenn Smoak, U.S. Bureau of Reclamation
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Prepared for Headquarters, U.S. Army Corps of Engineers

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	Problem Area		Problem Area
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

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Rehabilitation Research Program

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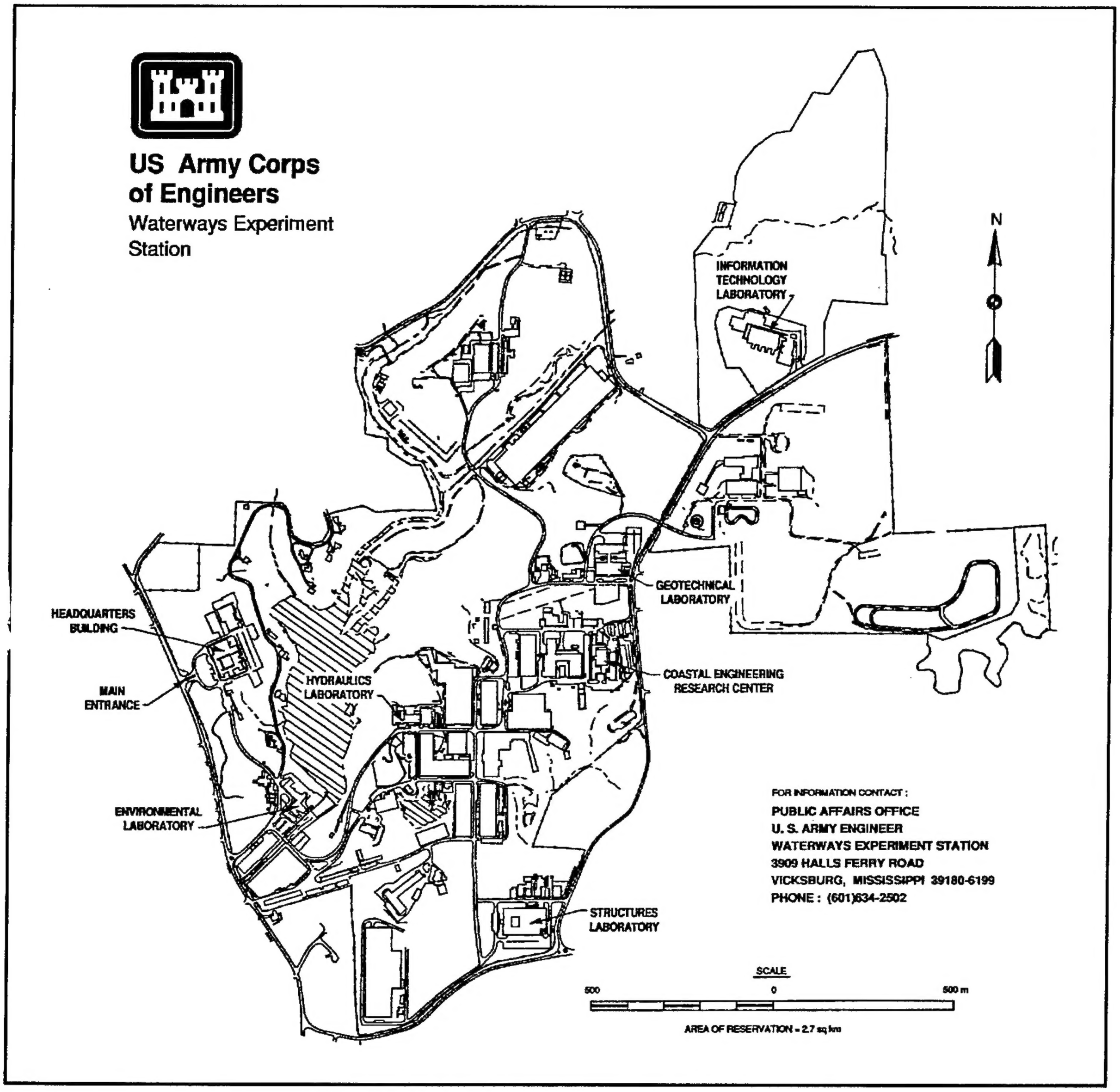

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Preface

The study reported herein was a cooperative testing program between the U.S. Army Engineer Waterways Experiment Station (WES) and the U.S. Bureau of Reclamation (USBR). The WES portion of the study was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Civil Works Research Work Unit 32637, "Evaluation of Existing Repair Materials and Methods," for which Mr. James E. McDonald, Structures Laboratory (SL), WES, is the Principal Investigator. This work unit is part of the Concrete and Steel Structures Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program.

Funds for the USBR portion of the study were provided by the Lower Colorado Regional Office for Research Program NMB-56 and Engineering Research ER-266. Mr. W. Glenn Smoak was the USBR Principal Investigator. This report was prepared by Mr. McDonald, Concrete and Materials Division (CMD), SL, Mr. Tony B. Husbands, retired, formerly Concrete Technology Division, and Mr. Smoak, Materials, Engineering, and Research Laboratory (MERL), USBR.

The REMR Technical Monitor is Mr. M. K. Lee, HQUSACE. Dr. Tony C. Liu (CERD-C) is the REMR Coordinator at the Directorate of Research and Development, HQUSACE. Mr. Harold C. Tohlen (CECW-O) and Dr. Liu serve as the REMR Overview Committee. Mr. William F. McCleese, WES, is the REMR Program Manager. Mr. McDonald is the Problem Area Leader for Concrete and Steel Structures. The WES portion of the study was under the general supervision of Dr. Paul F. Mlakar, Chief, CMD, and Mr. Bryant Mather, Director, SL. The BOR portion of the study was under the general supervision of Mr. Dave Harris, MERL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

1 Introduction

Background

The 17th Interagency Research Coordination Conference was held in Denver, CO, during October 1991. Discussions between representatives of the U.S. Army Engineer Waterways Experiment Station (WES) and the U.S. Bureau of Reclamation (USBR) indicated a mutual need to identify commercially available materials appropriate for thin repair of concrete surfaces. Both organizations have experienced problems in the field when performing these types of repairs. Consequently, planning was initiated for a cooperative effort to obtain the necessary test data and information on materials that could be used for these types of repairs.

In August 1992, a meeting was held at USBR to finalize the cooperative testing program. It was decided that USBR and WES would mutually select 10 to 15 commercially available materials with potential for relatively thin (<51-mm-(2-in.-) thick) repairs on concrete surfaces. The candidate materials would be evaluated in a two-phase study. The first phase would be laboratory tests to determine pertinent material properties, and the second phase would be to evaluate the performance of selected materials in field applications.

Objective

The objective of the cooperative investigation was to identify candidate materials with potential for thin repairs, conduct laboratory tests to determine pertinent material properties, and evaluate the performance of selected materials in field applications.

Scope

Eleven candidate materials were selected for the investigation. In the first phase of the study, each material was subjected to a suite of laboratory tests to

determine pertinent material properties. Results of this phase of the investigation are described herein.

2 Materials and Mixtures

Test methods and materials were mutually selected by USBR and WES. Except where otherwise noted, tests were conducted in accordance with American Society for Testing and Materials (ASTM) standard test methods (ASTM 1993). Testing was divided between the two laboratories as follows:

	Performing Laboratory	
	USBR	WES
Compressive strength, modulus of elasticity, and Poisson's ratio, (ASTM) C 39 (1993b)	X	X
Flexural strength, ASTM C 78 (1993c)		X
Pullout/tensile bond strength, USBR GR-83-14 (1983a)	X	
Resistance to freezing and thawing, ASTM C 666 (1993h), Procedure A		X
Sulfate exposure, USBR 4908 (1992a)	X	
Coefficient of thermal expansion, USBR 4910 (1992b)	X	
Underwater abrasion, ASTM C 1138 (1993i)		X
Water absorption by boiling water, ASTM C 642 (1993g)	X	
Curing shrinkage, USBR GR-83-10 (1983b)	X	
Drying shrinkage, ASTM C 157 (modified) (1993d)		X

(Continued)

	Performing Laboratory USBR	WES
Compressive creep, ASTM C 512 (1993f)	X	
Rapid chloride permeability, ASTM C 1202 (1993j)		X
Water-vapor transmission, ASTM E 96 (1993k)		X

Materials

The candidate repair materials were selected based on a review of test data, discussions with manufacturers and contractors, and examination of information that was already available at the USBR and WES. Data on more than 100 repair materials were reviewed. The 11 materials selected for evaluation are listed along with a description of each as obtained from the manufacturers' literature:

Material No./ Product/ Manufacturer	Material Description
P-1 BASF Corp BASF ND-614	The material is a latex admixture recommended for concrete that is to be used for patching. The latex is a styrene-butadiene with 48-percent solids by weight.
P-2 DN-74 Fosroc, Inc.	The material is a prepackaged blend of dry powders which requires only the addition of clean water to produce a light-weight, polymer-modified repair mortar. The material is based on portland cement, graded aggregates, lightweight fillers, polymers, fibers, and chemical additives.
P-3 Structural Concrete V/O Five Star Products, Inc.	The material is a prepackaged high-strength concrete repair mixture which requires only the addition of water. The material develops rapid strength gain and is formulated for vertical and overhead repair. It can be applied by shotcreting or hand-troweling.
P-4 Fibre Patch OV Gemite Products, Inc.	The material is a fast-setting prepackaged mortar that develops strength rapidly. It is formulated for vertical and overhead repair. It is a portland cement based, dry polymer, fiber-reinforced mortar.

(Continued)

Material No./ Product/ Manufacturer	Material Description
P-5 Octocrete IPA Systems, Inc.	The material is a prepackaged, one-component repair substance which requires only the addition of water. The material exhibits rapid strength gain and has a high ultimate strength. It is polymer modified and formulated for vertical and overhead repairs.
P-6 EMACO R300 Master Builders, Inc.	The material is a prepackaged, one-component, fast-setting, polymer-modified, cement-based mortar. It is recommended for patches 25 mm (1 in.) or less in thickness and can be used to repair both vertical and horizontal surfaces.
P-7 EMACO S88-C Master Builders, Inc.	The material is a rheoplastic, fiber-reinforced, one-component, high-strength, cement-based, shrinkage-compensated mortar. It can be applied by low-pressure spraying or hand-troweling.
P-8 Pyrament-XT Cement Pyrament Division made Lone Star Ind.	The material is a blended cement that is stated to be a complete cement which does not require admixtures to achieve high performance properties. Concrete with this cement develops high early strengths and high ultimate strengths.
P-9 Resist-A-Chem 7021 F Resist-A-Chem	This material is a prepackaged concrete mixture designed for application by the dry shotcrete process. The concrete mixture is composed of preblended silica fume, aggregate, and Type II portland cement.
P-10 Power Elite Gel Patch STO Powercrete	The material is a prepackaged repair material formulated for vertical and overhead repair. It is a cement-based, polymer-modified, fiber-reinforced blend.
P-11 Thoropatch Thoro Systems Products	The material is a two-component patching compound based on portland cement and acrylic polymer.

USBR and WES ordered the materials, when available, from local suppliers. Two of the materials, P-2 (DN-74) and P-6 (EMACO R300), had just been developed by the manufacturers and were designated as experimental. These two materials were shipped to the laboratories by the manufacturer. Material P-4 (Fibre Patch OV) could not be obtained from a local supplier; therefore, it was also obtained from the manufacturer. By ordering from local suppliers, different batches or lots of the materials were most likely obtained by the two laboratories.

Mixture Proportions

The manufacturers' recommended mixture proportions and mixing procedures were followed in the mixing of each repair material. In those cases where the manufacturer gave a range for the amount of mixing water, the amount used was established by the laboratories. The majority of the materials were mortars; however, three materials (P-1, P-8, and P-11) contained coarse aggregate. The USBR prepared and shipped both the fine and coarse aggregate to WES so that both laboratories would be using the identical aggregate systems. The coarse aggregate was a 9.5-mm (⅜-in.) nominal maximum-size siliceous crushed stone, and the fine aggregate was a natural sand meeting the requirements of ASTM C 33-93 (1993a). Mixture proportions, based on a 45.4-kg (100-lb) batch, were as follows:

Mortars

Material	Dry Material, kg (lb)	Water, kg (lb)
P-2	38.98 (85.94)	6.38 (14.06)
P-3	39.30 (86.65)	6.06 (13.35)
P-4	38.36 (84.56)	7.00 (15.44)
P-5	37.54 (82.77)	7.82 (17.23)
P-6	40.57 (89.43)	4.79 (10.57)
P-7	40.21 (88.65)	5.15 (11.35)
P-9	39.24 (86.51)	6.12 (13.49)
P-10	40.71 (89.75)	4.65 (10.25)

Concretes

Material	Weight, kg (lb)
Mixture P-1	
Type II portland cement	7.54 (16.63)
Water	1.55 (3.42)
Latex admixture	2.34 (5.15)
Fine aggregate	19.65 (43.33)
Coarse aggregate	14.27 (31.47)
Mixture P-8	
Blended cement	8.24 (18.17)
Water	3.13 (6.91)
Fine aggregate	19.7 (43.50)
Coarse aggregate	14.25 (31.42)
Mixture P-11	
Cement-based material	28.42 (62.66)
Coarse aggregate	12.47 (27.49)
Acrylic latex	4.47 (9.85)

Curing

Test specimens cast from the polymer-modified materials were left in the molds and covered with plastic or approved curing compound for the first 24 hr. The specimens were then stored in laboratory air until testing, typically at 28 days. The four materials that did not contain a polymer (P-3, 7, 8, and 9) were moist cured in the fog room at not less than 95-percent relative humidity and 23 +(-) 1.7 °C until the time of testing.

Test Methods

Specimen preparation and testing procedures for the various laboratory tests are described in the following paragraphs. Tests were conducted in accordance with standardized tests except where otherwise noted.

Compressive strength, modulus of elasticity, and Poisson's ratio

These material properties were determined by both the USBR and WES laboratories. Six 76- by 152-mm (3- by 6-in.) cylinders were cast from each of the repair materials for compression tests. All test specimens were air dried for 24 hr before testing so that strain gauges could be bonded to the specimens. The compressive strength of the specimens was determined according to ASTM C 39-93a (ASTM 1993b). The modulus of elasticity and Poisson's ratio were determined according to ASTM C 469-87a (ASTM 1993e).

Additional cylinders were fabricated from each repair material and placed in an ambient temperature water bath for periods of 18 and 26 months. These specimens were then tested in compression and their modulus of elasticity and Poissons ratio computed to determine if long-term soaking in water resulted in a change of strength and elastic properties.

Flexural strength

Three 89- by 114- by 406-mm (3-1/2- by 4-1/2- by 16-in.) beams were cast from a batch of each material. Flexural strengths were determined according to ASTM C 78-84 (ASTM 1993c) at 28 days.

Pullout/tensile bond strength

The pullout/tensile bond strength of the repair materials was determined using an LOK-Test device as described in USBR report No. GR-83-14 (USBR 1983a). For this test procedure, an overlay of the repair material was placed on a sand

blasted concrete base slab and cured as previously described. A 51-mm- (2-in.-) diam core was then drilled through the repair material 38 mm (1-1/2 in.) into the base concrete. A steel plate was then bonded to the top of the repair core with high-strength epoxy resin. A threaded hole in the plate was used to attach the LOK-Test device. Load was applied to the plate by a hydraulic jack until a tensile failure occurred. The tensile strength and failure location was noted and averaged for three test specimens of each repair material.

Resistance to freezing and thawing

The resistance of each material to damage from cycles of freezing and thawing was determined according to ASTM C 666-92, Procedure A (ASTM 1993h). Three 89- by 114- by 406-mm (3-1/2- by 4-1/2- by 16-in.) beams were prepared from each material. After curing as previously described, specimens were stored in lime-saturated water for 14 days before the test was started. Test specimens were subjected to a maximum of 300 cycles of freezing and thawing.

Resistance to sulfate exposure

The length change of hardened test specimens exposed to alkali sulfates was determined according to USBR 4908-92, Method C, (USBR 1992a). Three 76- by 152-mm (3- by 6-in.) cylinders were prepared from each material. After the curing period, specimens were placed in a 2.1-percent sodium-sulfate solution where they underwent alternating cycles of 16 hours soaking at about 22.8 °C (73 °F) and 8 hours drying in air under a forced draft at about 54.4 °C (130 °F). The length change of the specimens was monitored for a period of 206 days.

Coefficient of thermal expansion

The coefficient of linear thermal expansion was determined according to USBR 4910-92 (USBR 1992b). Tests were conducted on six 51- by 102-mm (2- by 4-in.) cylinders cast from each repair material.

Abrasion resistance

Two specimens of each material were cast for testing according to ASTM C 1138-89, Standard Test Method for Abrasion Resistance of Concrete (Underwater Method) (ASTM 1993i). Following the 28-day curing period, specimens were soaked in water for 7 days before the tests were started. Volume loss for each specimen was determined periodically during the 72-hr test period.

Water absorption

The 10-min and 5-hr boiling water absorption was determined in accordance with ASTM C 642-90 (ASTM 1993g) on two 76- by 152-mm (3- by 6-in.) cylinders prepared with each repair material.

Curing shrinkage

Curing shrinkage was determined in accordance with the test method and equipment described in USBR report No. GR-83-10 (USBR 1983b). In this test, a proximity transducer was used to measure the relative movement between two suspended plates that were embedded vertically in a 51-mm- (2-in.-) thick, freshly placed, repair material overlay on a conventional concrete base slab. A thermocouple buried in the overlay material recorded the maximum hydration temperature and the time of occurrence. Data were recorded until the repair material exhibited essentially no further dimensional change.

Drying shrinkage

Four 25- by 25- by 286-mm (1- by 1- by 11-1/4-in.) beams with an effective gauge length of 254 mm (10 in.) were cast from each of the repair mortars. Similar specimens with a 76- by 76-mm (3- by 3-in.) cross section were cast from the three materials that contained coarse aggregate (P-1, 8, and 11). Following casting, the molds containing the test specimens were placed in a moist curing cabinet for 47 hr. The specimens were removed from the molds, and the initial length was measured 48 hr after casting. The beams were then stored in laboratory air at 22.8 °C (73 °F) and 50-percent relative humidity. Drying shrinkage of the beams was monitored for a period of at least 28 days by measuring the length change according to ASTM C 157-93 (ASTM 1993d).

Creep

Two 152- by 305-mm (6- by 12-in.) cylinders were prepared from each repair material and cured for 28 days. The specimens were then subjected to a sustained compressive load of 5.5 MPa (800 psi) and tested for creep in accordance with ASTM C 512-87 (ASTM 1993f). Strain measurements were made periodically during the 612-day loading period. Unloaded control cylinders were also monitored during this period.

Chloride permeability

Three 102- by 203-mm (4- by 8-in.) cylinders were cast from each of the materials. Following the 28-day curing period, a 51-mm (2-in.) slice was removed from the top of each cylinder by sawing. The test specimens were then prepared and tested according to ASTM C 1202-91 (ASTM 1993j).

Water-vapor transmission

The water-vapor transmission (WVT) of each material was determined according to ASTM E 96-92 (ASTM 1993k). The apparatus described in the test method for large thick specimens was used for the test, except that the size was reduced to 190 by 190 mm (7-1/2 by 7-1/2 in.) as opposed to the 289- by 289-mm (11-3/8- by 11-3/8-in.) size given in the test method. The test apparatus was constructed from 12.7-mm- (½-in.-) thick plexiglass. The 12.7-mm- (½-in.-) thick specimens were cast in polyethylene forms. The coarse aggregate was omitted from materials P-1, 8, and 11, and the mortar portion was tested for WVT. The mold and specimen ready for test are shown in Figures 1 and 2.

Restrained shrinkage test

After most of the testing was completed, WES decided to test some of the materials for restrained shrinkage. The ring-type specimen used for this test was similar to that described by Rizzo and Sobelman (1989). The material in those tests was cast around a rigid steel pipe. After demolding for 1 hr following final set, specimens were placed in laboratory air and observed for cracking. WES chose to use solid 102-mm- (4-in.-) diam concrete cylinders rather than steel pipe to provide restraint. These cylinders were approximately 1 year old and had been stored in laboratory air for at least 6 months. The cylinders were cut into 57-mm (2-1/4-in.) slices. A form was made by cutting 51-mm- (2-in.-) wide strips from a thick-wall PVC pipe that had an inside diameter of 203 mm (8 in.) The outside edges of the concrete slices were abraded to obtain a good bond with the material. In order to prevent the cylinder from moving when the material was placed, a few small beads of silicon caulk were placed on one of the flat sides of the cylinder so that the cylinder could be adhered to the top of a board. The PVC plastic ring was then placed around the cylinder and braced. The mold for preparing the test specimen is shown in Figure 3. The material was allowed to moist cure for 48 hr before the test specimen was stripped from the mold. The specimen was then placed into laboratory air and observed for cracking each working day. Nine of the materials were tested, and two specimens were prepared from each material from two separate batches.

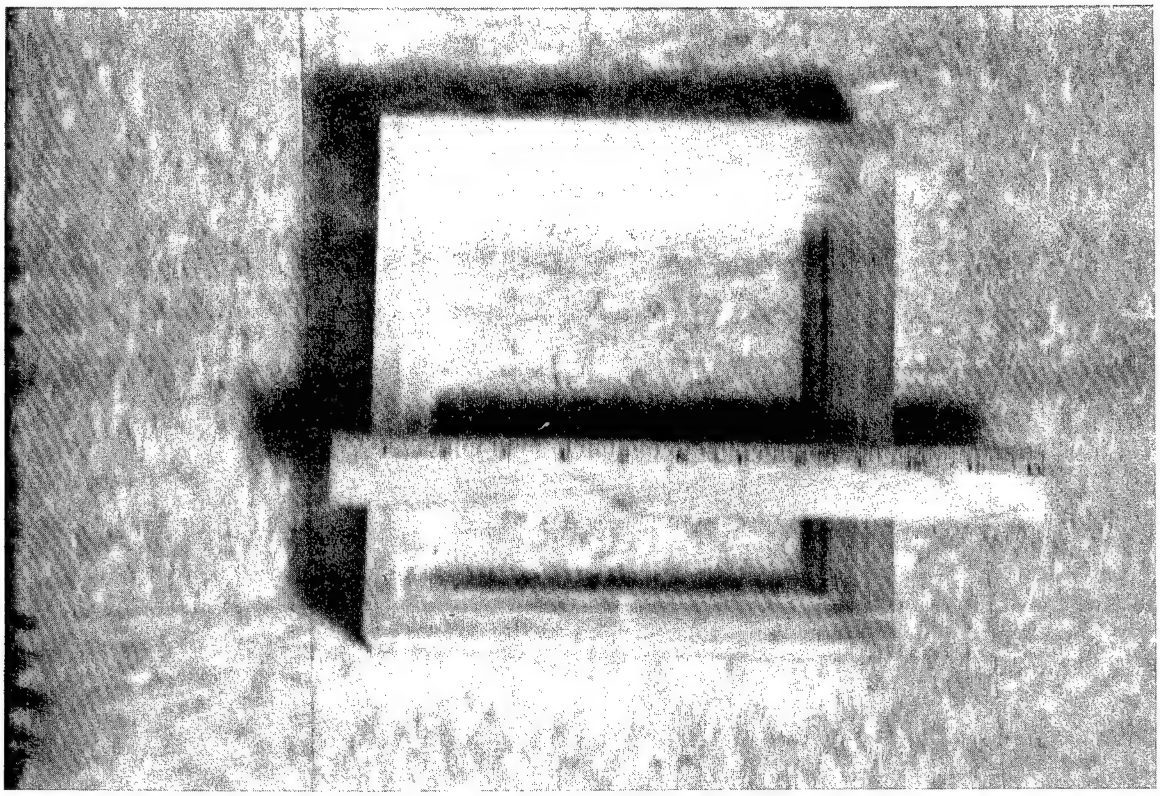

Figure 1. Mold for water-vapor transmission test

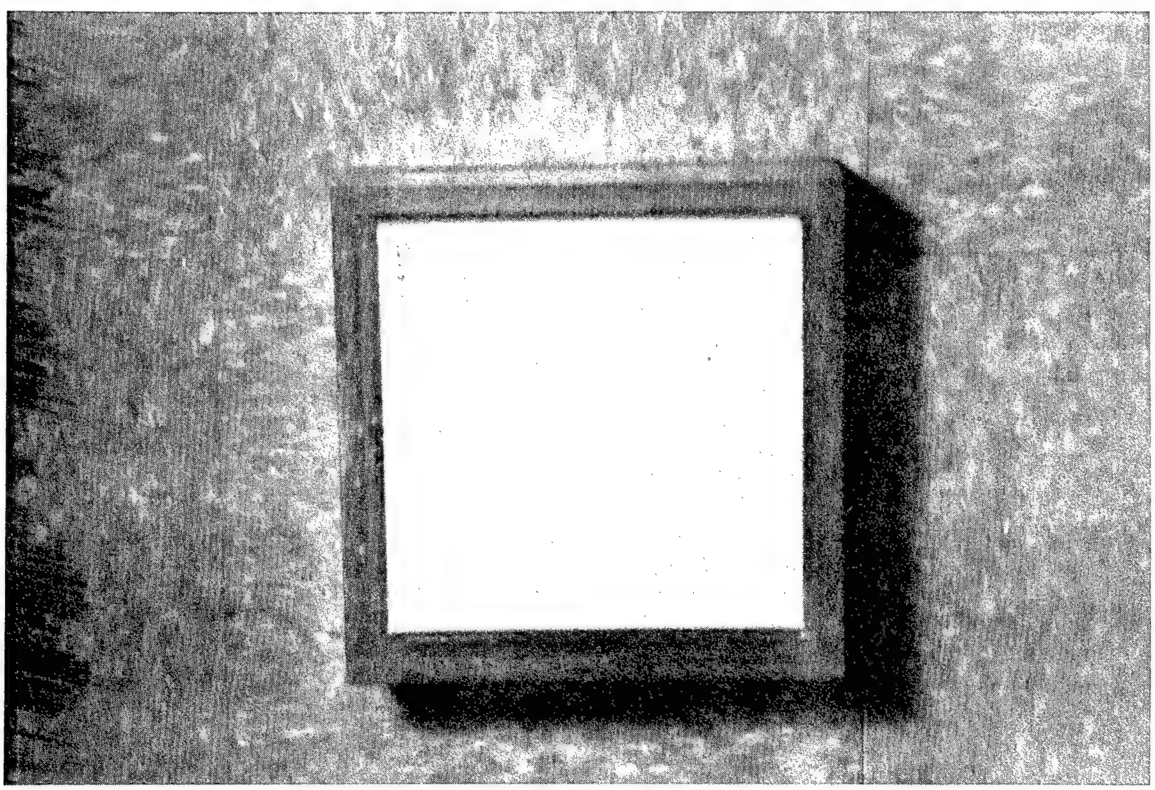

Figure 2. Completed water-vapor transmission test specimen

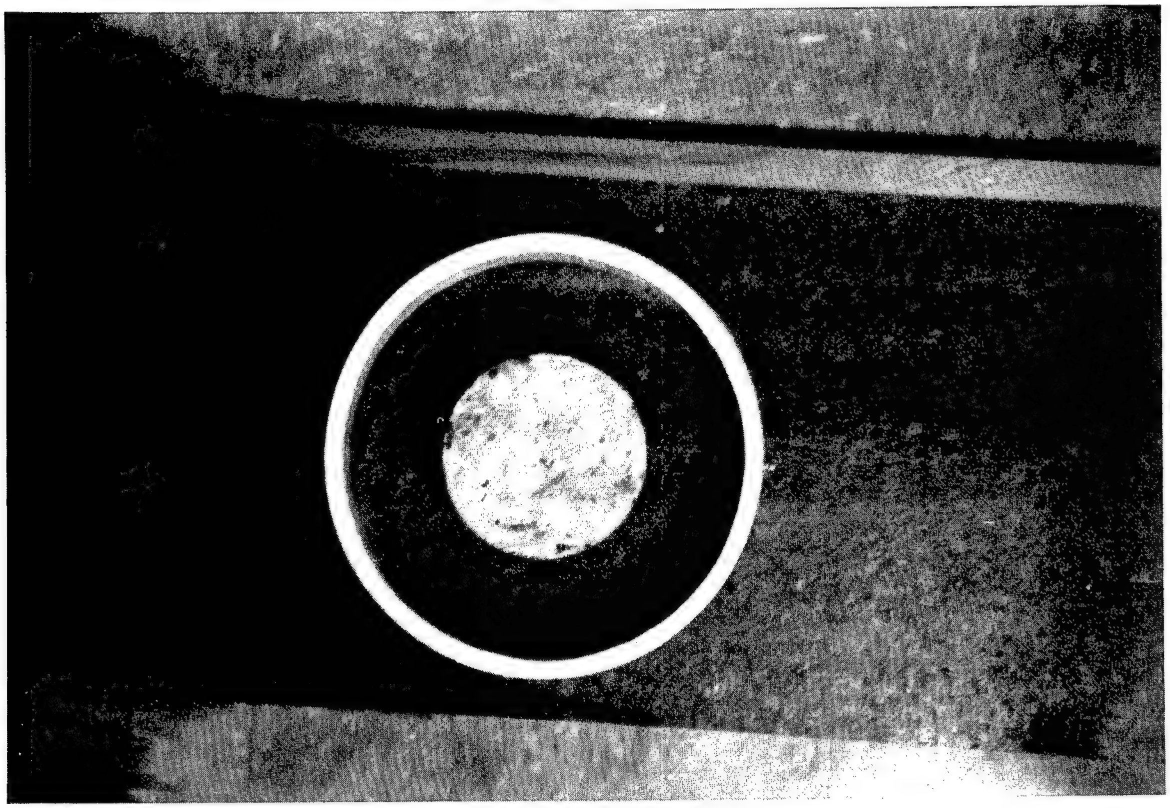

Figure 3. Mold for restrained shrinkage test specimen

3 Test Results

Compressive Strength, Modulus of Elasticity, and Poisson's Ratio

Test results for compressive strength, modulus of elasticity, and Poisson's ratio obtained by both laboratories are shown in Table 1. The average 28-day compressive strengths of the materials ranged from a low of 32.3 MPa (4,680 psi) for P-4 (Fibre Patch OV) to a high of 82.5 MPa (11,970 psi) for P-7 (EMACO S88-C). Typically, compressive strengths around 34.5 MPa (5,000 psi) will be adequate for most repairs unless exposure conditions dictate the use of higher strength materials. There was a greater difference than expected between the two laboratories' compressive strength test results for the same material. The greatest differences were for materials P-1, 3, 5, 7, and 11). The differences in test results between laboratories was attributed to the different batches of material obtained for testing. WES had to use ice water for mixing P-5 to increase the initial time of setting. USBR did not experience this problem with the material. WES also noted that P-11 had a large amount of entrapped air in the hardened material. Later in the study, a defoamer was added to a small batch of the material, and a compressive strength of 39.7 MPa (5,760 psi) was obtained, which was close to the 37.4 MPa (5,430 psi) value obtained by USBR. It was believed that either the latex was bad for the batch of material obtained by WES or that the defoamer had decomposed with time. When reviewing mixture proportions, it was discovered that WES used approximately 0.9 kg (2 lb) less water in material P-3 than the 6.06 kg (13.35 lb) used by USBR. The resultant lower water-cement ratio (w/c) may account for the higher 28-day strengths obtained by WES.

The 28-day modulus of elasticity test results ranged from a low of 1.16×10^4 MPa (1.68×10^6 psi) to a high of 3.61×10^4 MPa (5.23×10^6 psi). The modulus of elasticity of the polymer-modified materials P-1, 2, 4, 5, 6, 10, and 11 were generally lower compared to the other materials, as was expected. P-6 (EMACO R300) had a modulus of elasticity of 2.19×10^4 MPa (3.18×10^6 psi), which was similar to values of the materials that did not contain a polymer. The values for modulus of elasticity obtained by USBR and WES for material P-7 were 2.58 and 3.61×10^4 MPa (3.74 and 5.23×10^6 psi), respectively. This

Table 1
Results of Compressive Strength Tests

Material/Test Conditions	Compressive Strength, MPa (psi)		Modulus of Elasticity, MPa x 10^4 (psi × 10^6)		Poisson's Ratio	
	USBR	WES	USBR	WES	USBR	WES
P-1						
28 days	50.7 (7,360)	43.0 (6,230)	1.97 (2.85)	1.76 (2.55)	0.21	0.18
Water soaked						
18 mo	50.1 (7,260)		2.57 (3.73)		0.20	
26 mo		38.8 (5,630)		2.32 (3.37)		
P-2						
28 days	40.1 (5,820)	38.7 (5,610)	1.82 (2.64)	2.01 (2.92)	0.23	0.22
Water soaked						
18 mo	50.1 (7,270)		2.04 (2.96)		0.24	
26 mo		45.8 (6,640)		2.18 (3.16)		
P-3						
28 days	44.7 (6,490)	54.9 (7,960)	2.23 (3.24)	2.62 (3.80)	0.23	0.21
Water soaked						
18 mo	68.4 (9,920)		2.72 (3.94)		0.24	
26 mo		67.0 (9,720)		3.27 (4.74)		
P-4						
28 days	33.1 (4,810)	31.4 (4,560)	1.77 (2.56)	1.64 (2.38)	0.23	0.21
Water soaked						
18 mo	39.7 (5,760)		1.86 (2.70)		0.22	
26 mo		37.1 (5,380)		1.99 (2.89)		
P-5						
28 days	46.2 (6,700)	38.4 (5,570)	1.17 (1.70)	1.16 (1.68)	0.24	0.19
Water soaked						
18 mo	70.4 (10,210)		2.34 (3.40)		0.22	
26 mo		56.4 (8,180)		1.92 (2.78)		
P-6						
28 days	47.8 (6,940)	45.9 (6,660)	2.13 (3.09)	2.26 (3.28)	0.28	0.27
Water soaked						
18 mo	40.1 (5,810)		1.03 (1.50)		0.29	
26 mo		34.8 (5,050)		0.92 (1.33)		
P-7						
28 days	72.1 (10,460)	92.9 (13,480)	2.58 (3.74)	3.61 (5.23)	0.21	0.20
Water soaked						
18 mo	83.4 (12,090)		3.12 (4.53)		0.19	
26 mo		97.4 (14,130)		3.92 (5.69)		
P-8						
28 days	63.1 (9,150)	67.6 (9,800)	2.49 (3.61)	2.51 (3.64)	0.20	0.20
Water soaked						
18 mo	65.2 (9,450)		3.04 (4.41)		0.20	
26 mo		56.3 (8,170)		3.05 (4.43)		
P-9						
28 days	39.2 (5,680)	38.2 (5,540)	2.55 (3.70)	2.67 (3.87)	0.19	0.19
Water soaked						
18 mo	51.1 (7,410)		2.42 (3.51)		0.16	
26 mo		46.7 (6,770)		2.96 (4.30)		
P-10						
28 days	58.7 (8,520)	56.3 (8,160)	1.94 (2.81)	1.95 (2.83)	0.22	0.22
Water soaked						
18 mo	58.3 (8,460)		2.16 (3.13)		0.23	
26 mo		51.2 (7,430)		2.12 (3.08)		
P-11						
28 days	37.4 (5,430)	27.6 (4,000)	2.05 (2.98)	1.83 (2.65)	0.19	0.17
Water soaked						
18 mo	35.5 (5,150)		2.46 (3.57)		0.24	
26 mo		33.4 (4,840)		2.42 (3.51)		

difference was greater than for most materials tested. The manufacturer reported a modulus of elasticity of 3.0×10^4 MPa (4.3×10^6 psi) for this material.

The USBR test results indicated that the compressive strength of all materials after 18 months submerged in water was similar to or higher than the 28-day strengths, with the exception of material P-6 (EMACO R300). This material exhibited a strength that was lower by 7.8 MPa (1,130 psi). Similarly, material P-6 exhibited a strength that was lower by 10.4 MPa (1,510 psi) after 26 months submerged in water at WES. In each case, the modulus of elasticity of material P-6 was lower by more than 50 percent after extended submersion. The WES tests indicated that the compressive strengths of two additional materials, P-1 and P-8, were significantly lower after extended submersion; however, in each case the modulus of elasticity was appreciably higher following submersion.

Flexural Strength

The flexural strength test results (Table 2) for the materials ranged from a low of 4.0 MPa (585 psi) for P-9 (Resist-A-Chem 7021 F) to a high of 11.5 MPa (1,675 psi) for P-7 (EMACO S88-C). The flexural strengths of all materials, with the exception of P-8, were within the range of 11 to 15 percent of the compressive strength. The flexural strength of material P-8 (Pyrament-XT) was 9 percent of the compressive strength. The flexural strengths for the polymer-modified materials were generally lower than would have been expected for some of these materials. Polymer additives usually increase both flexural and tensile strengths of cementitious mortars. The flexural strengths of the polymer-modified materials ranged from 4.2 to 6.2 MPa (605 to 905 psi) with an average strength of 5.2 MPa (760 psi). Materials P-7 (EMACO S88-C) and P-3 (Structural Concrete V/O), which did not contain polymers, exhibited the highest flexural strengths.

Table 2
Results of Flexural Strength Tests

	Flexural Strength,	
Material	MPa (psi)	% of Comp. Strength
P-1	5.7 (825)	13
P-2	5.3 (765)	14
P-3	8.0 (1,155)	15
P-4	4.5 (655)	14
P-5	4.7 (680)	12
P-6	6.2 (905)	14
P-7	11.5 (1,675)	12
P-8	6.3 (910)	9
P-9	4.0 (585)	11
P-10	6.1 (885)	11
P-11	4.2 (605)	15

The strength test results obtained by the two laboratories were compared to the results found in the technical data sheets obtained from the manufacturer (Table 3). Most manufacturers reported compressive strengths and flexural strengths, but there was very little information available in the technical data sheets for modulus of elasticity and Poisson's ratio. There was a large difference in the laboratories' and the manufacturers' compressive strength test results for Fibre Patch OV (P-4). There was a discrepancy between flexural strength test results, especially for the polymer-modified materials Fibre Patch OV, Power Elite Gel Patch, and Thoropatch (P-4, 10, and 11). Some of the flexural strength values obtained by WES were approximately one-third that of the values reported by the manufacturer. It should be noted that the manufacturer's specimen sizes, curing conditions, and test methods often differed from those described herein.

Table 3
Comparison of Laboratories' and Manufacturers' Test Results

Material	Compressive Strength, MPa (psi)		Flexural strength, MPa (psi)	
	Laboratory[1]	Manufacturer	Laboratory	Manufacturer
P-1	46.9 (6,800)	--	5.7 (825)	--[2]
P-2	39.4 (5,720)	--	5.3 (765)	--
P-3	49.8 (7,220)	41.4 (6,000)	8.0 (1,155)	--
P-4	32.3 (4,680)	54.2 (7,860)	4.5 (655)	8.9 (1,290)
P-5	42.3 (6,140)	41.4 (6,000)	4.7 (680)	--
P-6	46.9 (6,800)	48.3 (7,000)	6.2 (905)	--
P-7	82.5 (11,970)	75.8 (11,000)	11.5 (1,675)	9.0 (1,300)
P-8	65.4 (9,480)	68.9 (10,000)	6.3 (910)	8.3 (1,200)
P-9	38.7 (5,610)	48.3 (7,000)	4.0 (585)	--
P-10	57.5 (8,340)	60.7 (8,800)	6.1 (885)	13.1 (1,900)
P-11	32.5 (4,720)	34.5 (5,000)	4.2 (605)	10.3 (1,500)

[1] Average of USBR and WES 28-day test results.
[2] Manufacturer reported that the flexural strength was twice that of a portland cement mortar.

Pullout/Tensile Bond Strength

The results of the pullout/tensile bond strength tests are summarized in Table 4. All materials exhibited a tensile strength in excess of 2.1 MPa (300 psi) which should be adequate for most applications. Seven materials exhibited tensile strengths sufficient to cause failure in the base concrete. The average failure stress in these cases was 3.6 MPa (515 psi). Tensile failures for the remaining materials occurred, at least in part, at the joint. The average failure stress in these cases was 3.2 MPa (465 psi).

Table 4 Results of Pullout/Tensile Bond Strength Tests			
Material	Tensile Strength[1], MPa (psi)	Failure Location	Remarks
P-1	5.5 (800)	Base concrete	
P-2	2.8 (410)	Base concrete	
P-3	2.9 (415)	Base concrete	Extensive cracking radiating from over-cored surface and penetrating surface
P-4	3.7 (535)	Base concrete	
P-5	3.0 (435)	At joint	Extensive cracking radiating from over-cored surface and penetrating surface
P-6	3.0 (430)	Base concrete	
P-7	3.0 (440)	Base concrete	
P-8	4.0 (585)	Base concrete	
P-9	4.0 (575)	Joint and base concrete	
P-10	3.4 (500)	Joint and repair material	Extensive cracking radiating from over-cored surface and penetrating surface
P-11	2.4 (350)	Joint and base concrete	102 mm (4 in.) of hairline cracking on top surface

[1] Average of 3 tests on 51-mm- (2-in.-) diam specimens.

Resistance to Freezing and Thawing

The results of the freezing-and-thawing tests are shown in Figures 4 through 14.

Only four materials exhibited a relative dynamic modulus of 60 percent or higher after 300 cycles of freezing and thawing under the severe exposure conditions of this test. These materials P-1 (BASF ND-614), P-6 (EMACO R300), P-8 (Pyrament-XT), and P-11 (Thoropatch) are considered to have satisfactory resistance to freezing and thawing. Two of the three test specimens for material P-8 had a relative dynamic modulus of less than 60 percent after approximately 240 cycles, indicating that this material could experience some problems with freezing and thawing. However, this material was evaluated by WES in a prior study, and the specimens prepared from this cement in those tests exhibited excellent resistance to freezing and thawing.

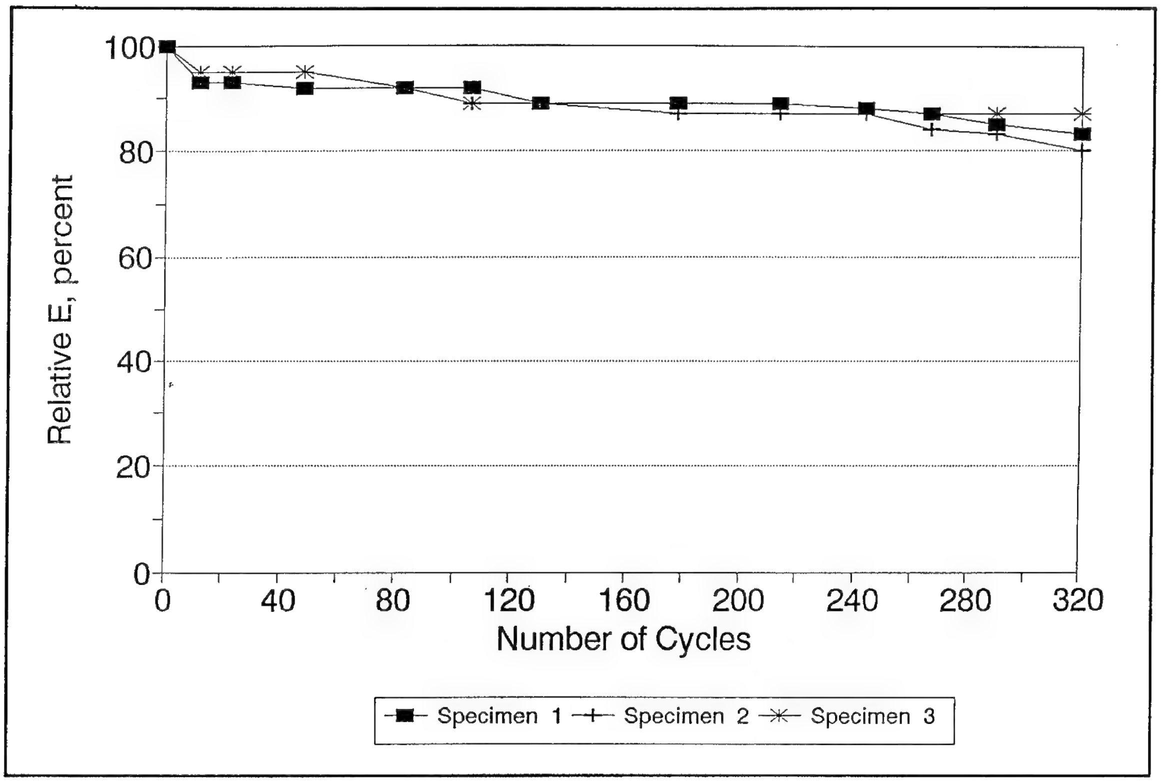

Figure 4. Results of freezing-and-thawing test on material P-1

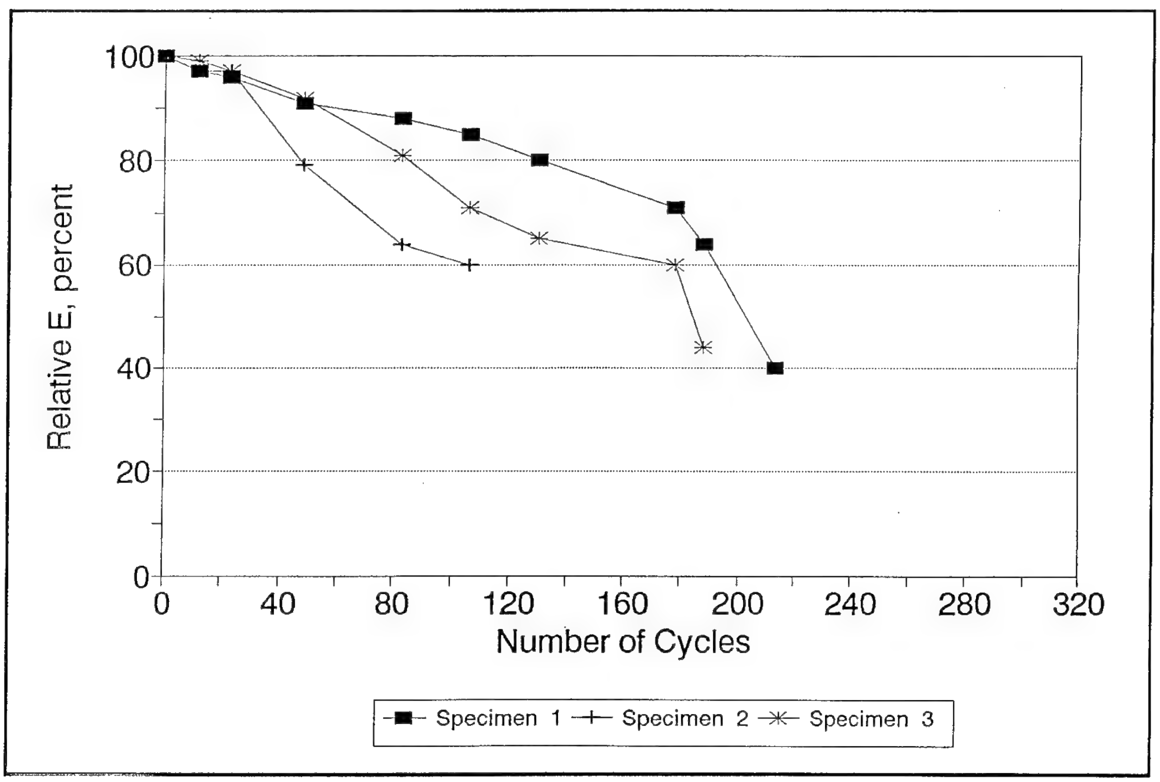

Figure 5. Results of freezing-and-thawing test on material P-2

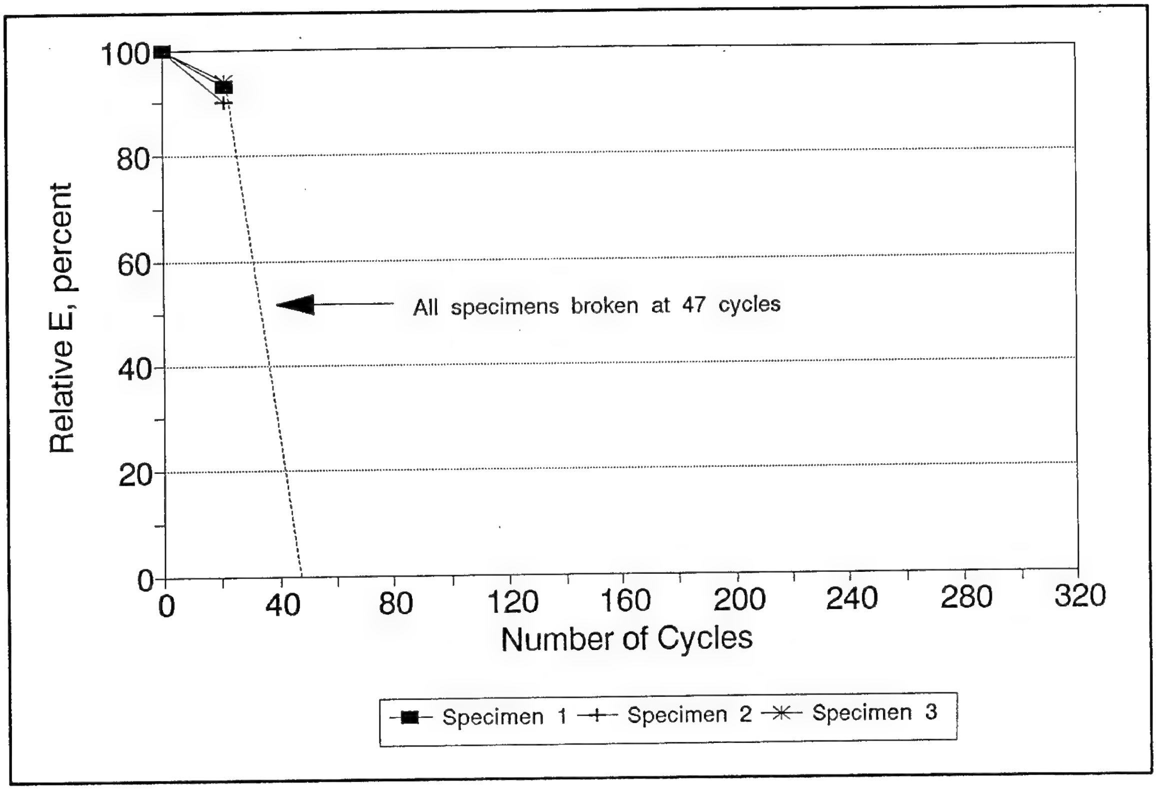

Figure 6. Results of freezing-and-thawing test on material P-3

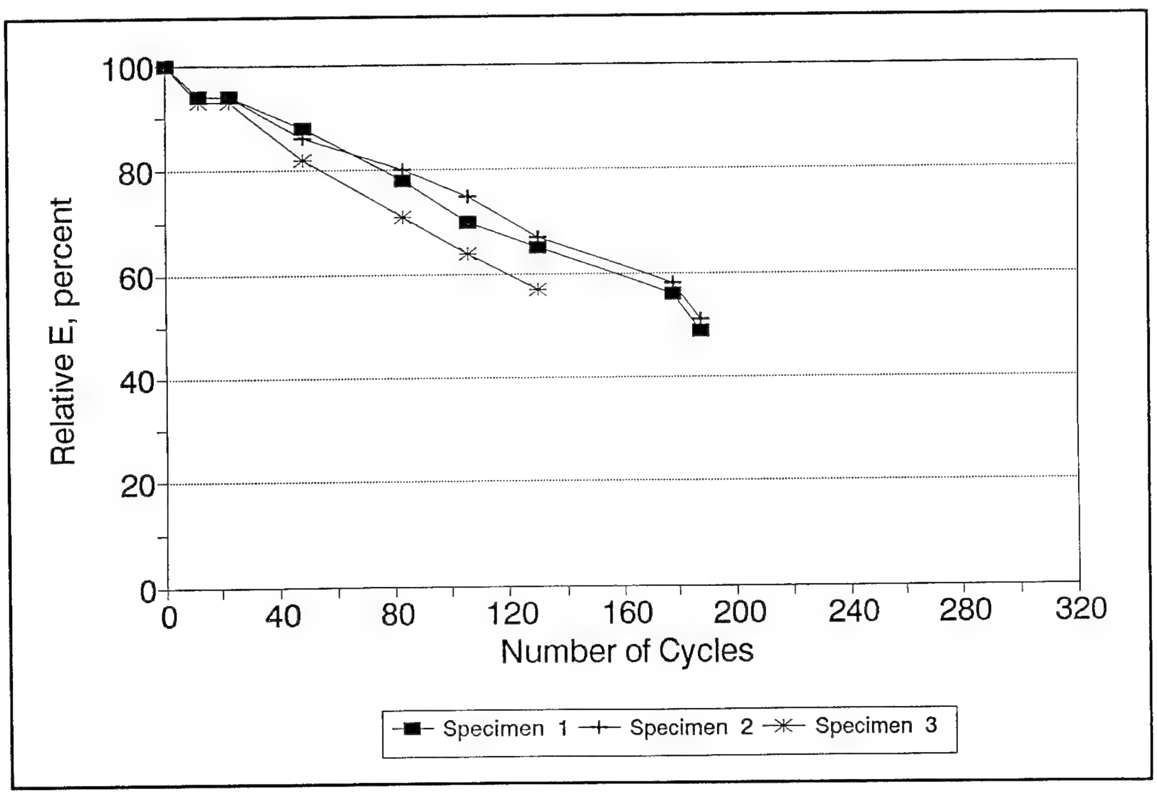

Figure 7. Results of freezing-and-thawing test on material P-4

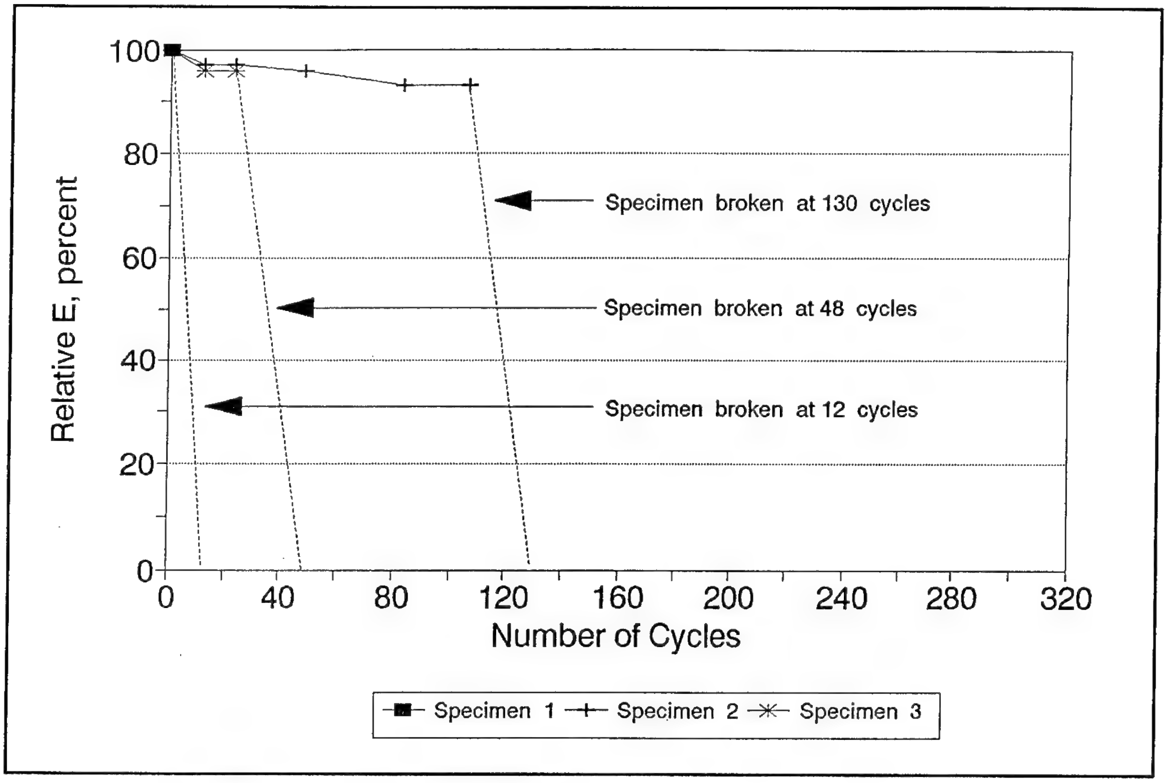

Figure 8. Results of freezing-and-thawing test on material P-5

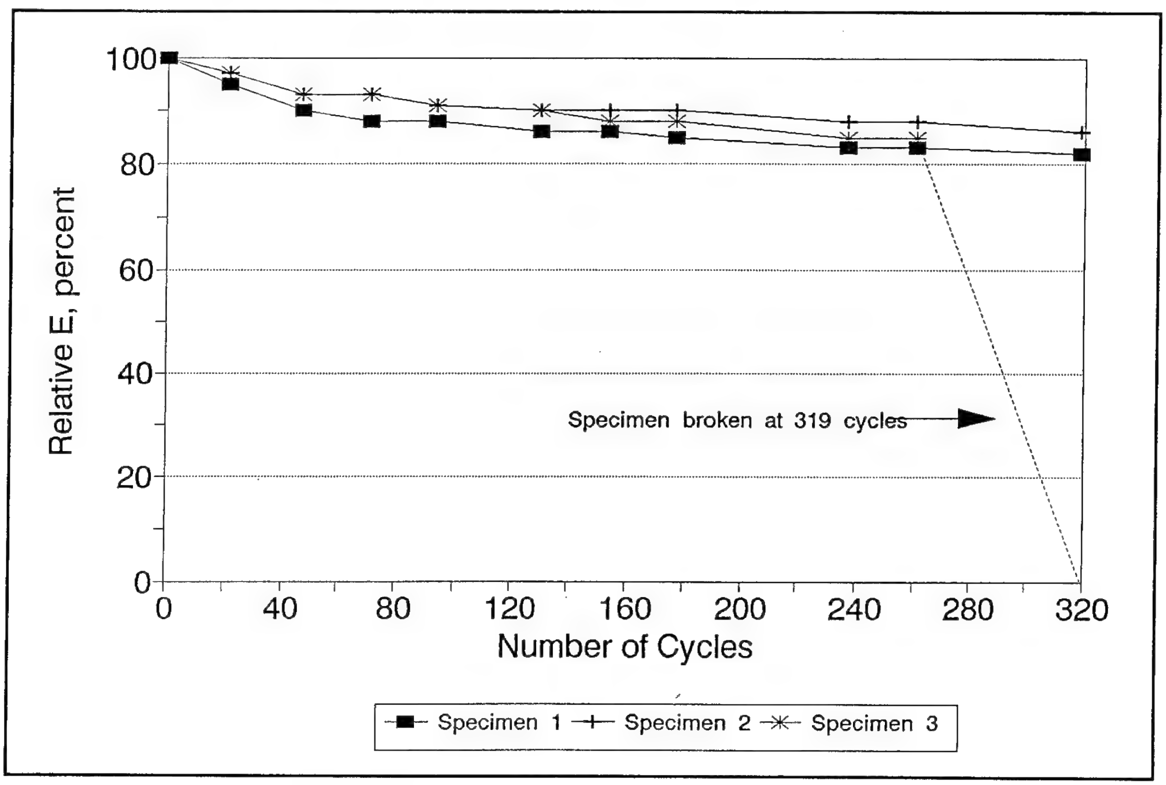

Figure 9. Results of freezing-and-thawing test on material P-6

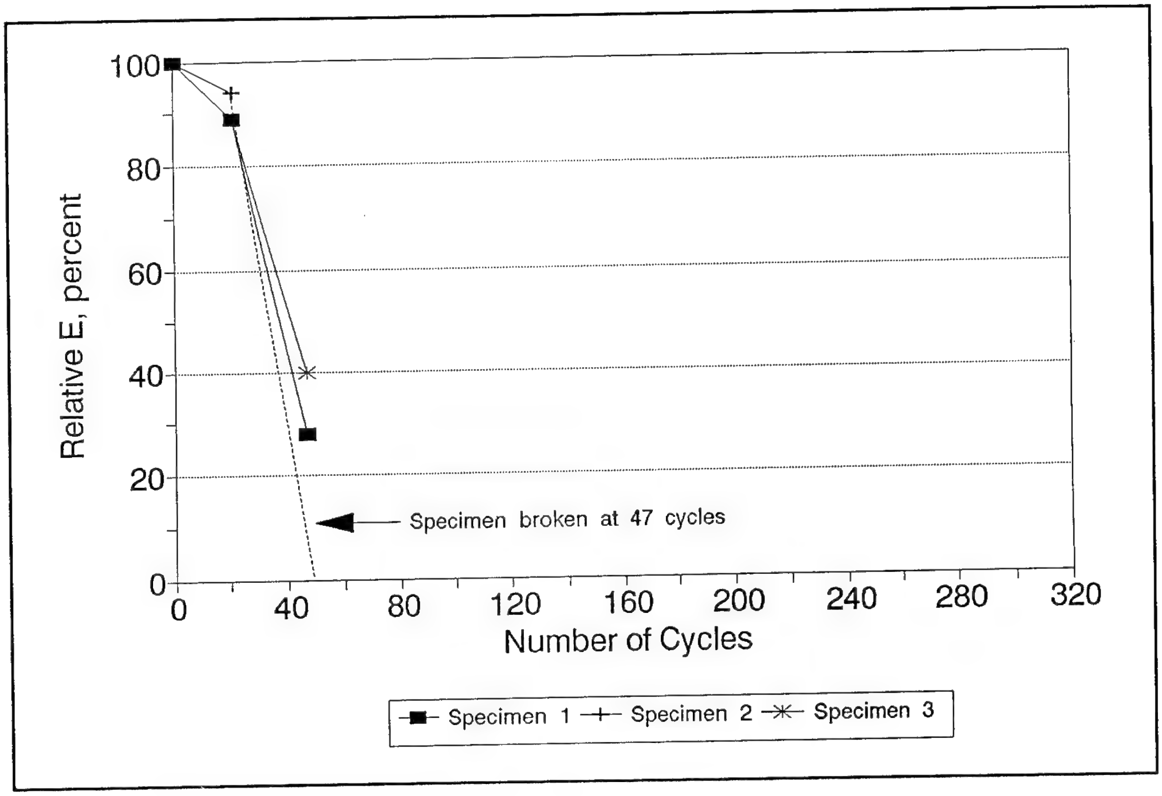

Figure 10. Results of freezing-and-thawing test on material P-7

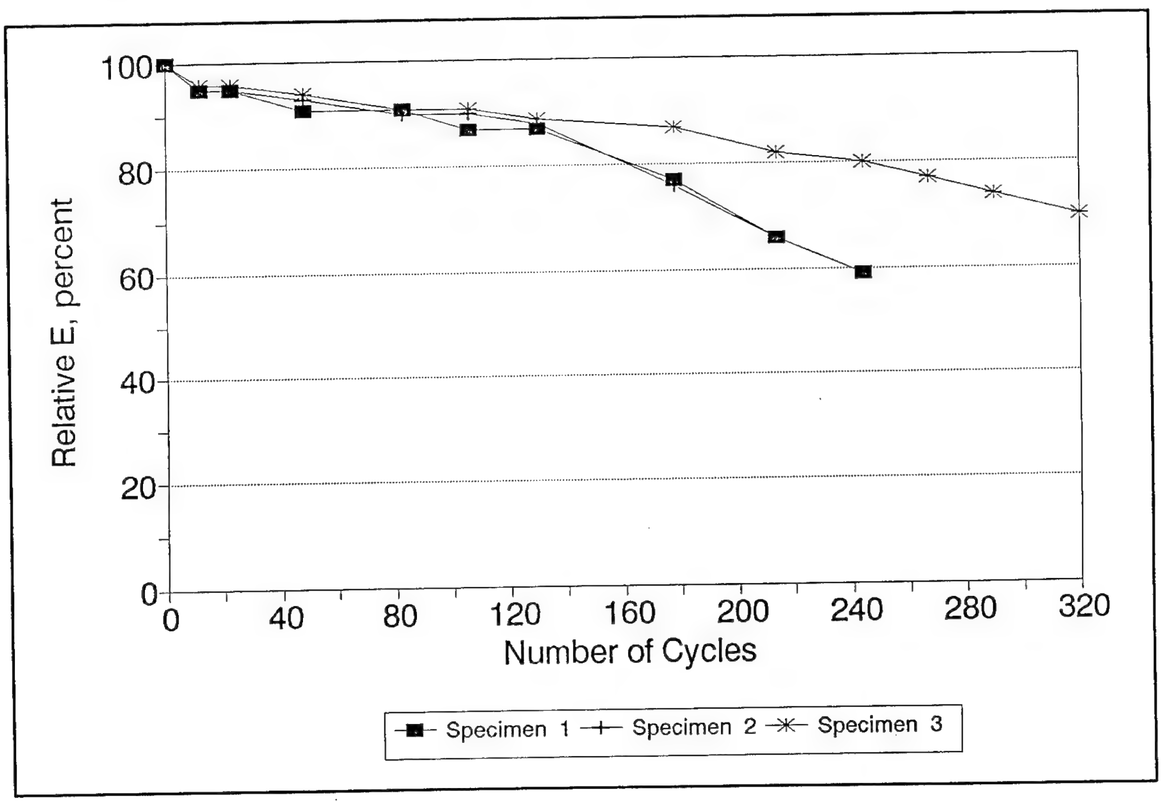

Figure 11. Results of freezing-and-thawing test on material P-8

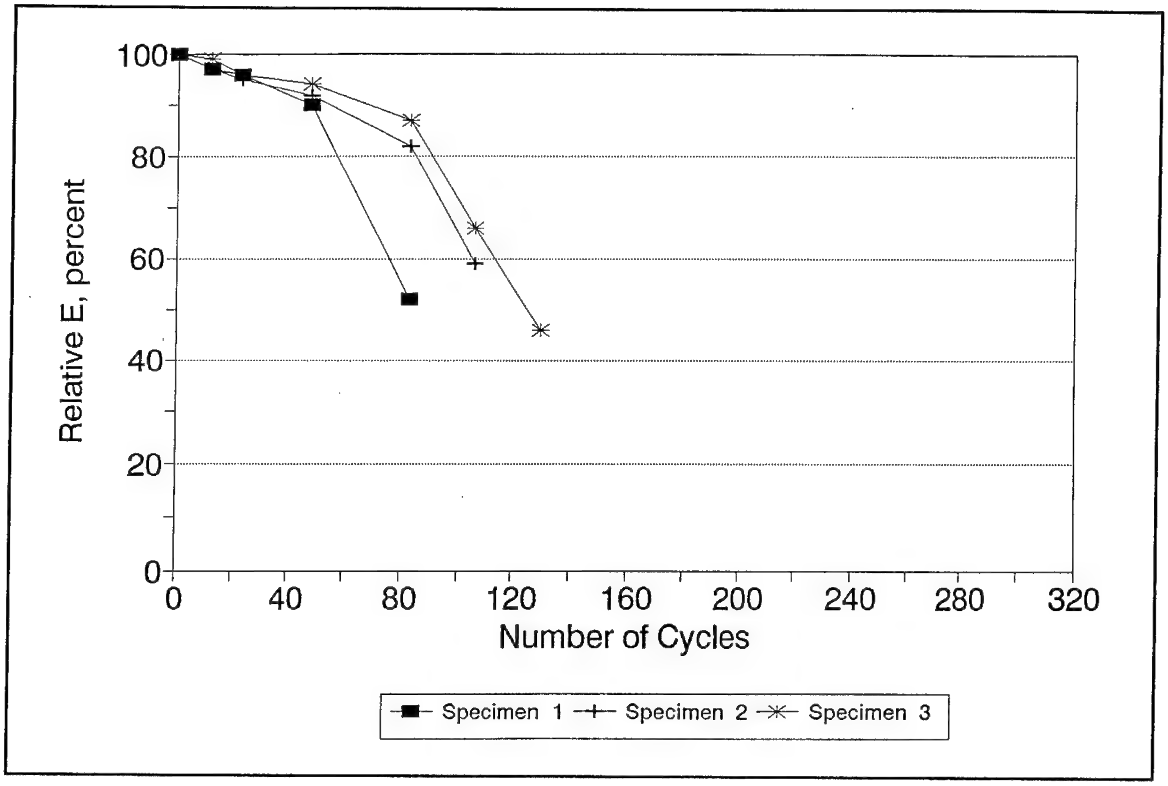

Figure 12. Results of freezing-and-thawing test on material P-9

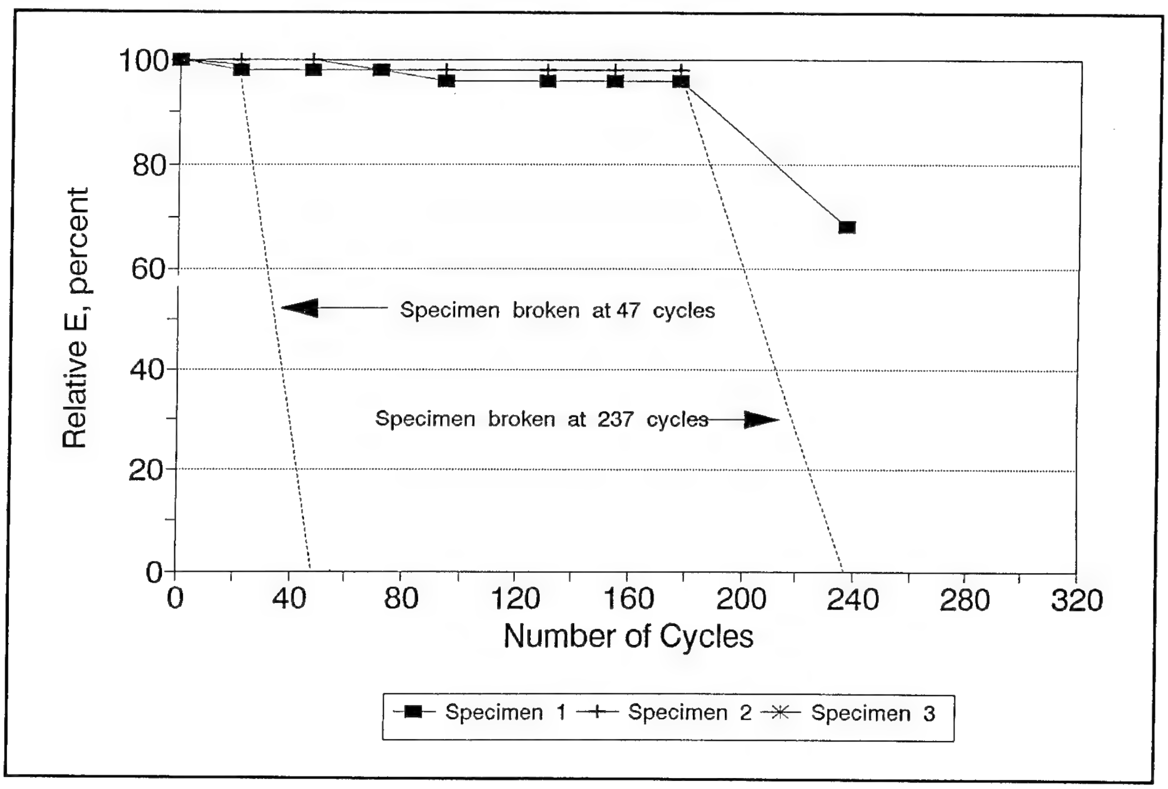

Figure 13. Results of freezing-and-thawing test on material P-10

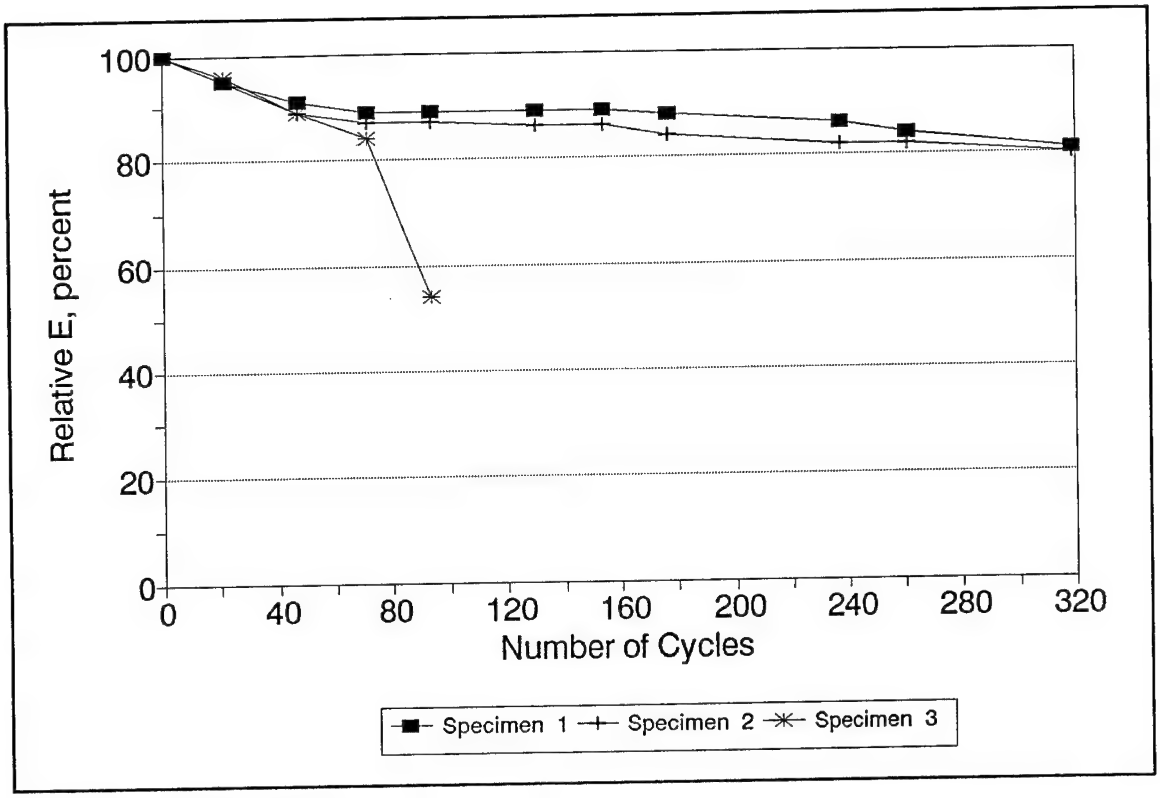

Figure 14. Results of freezing-and-thawing test on material P-11

Resistance to Sulfate Exposure

The results of the sulfate exposure tests are shown in Table 5. Material P-6 (EMACO R300) exhibited by far the highest expansion (4.745 percent after 206 days). Any material exhibiting an expansion in excess of 0.50 percent is considered to have failed this test. Material P-6 should not be used in environments contaminated with sulfates. Materials P-1 (BASF ND-614), P-4 (Fibre Patch OV), P-8 (Pyrament-XT), and P-10 (Power Elite Gel Patch) exhibited good stability in these tests; however, none of the materials, with the exception of P-6, failed this accelerated test.

Coefficient of Thermal Expansion

Results of the coefficient of thermal expansion tests are shown in Table 6. Six specimens were tested and the results were averaged for each material. The coefficients of expansion ranged from 6.70 millionths/°C (3.72 millionths/°F) for material P-8 (Pyrament-XT) to 14.22 millionths/°C (7.90 millionths/°F) for material P-6 (EMACO R300). Typically, the coefficient of expansion for conventional concrete ranges from about 9 to 11 millionths/°C (5 to 6 millionths/°F).

Table 5
Results of Accelerated Sulfate Exposure Tests

Material	Expansion[1], %	Test Duration, Days
P-1	0.000	206
P-2	0.014	166
P-3	0.041	206
P-4	-0.003[2]	206
P-5	0.090	206
P-6	4.745[3]	206
P-7	0.025	206
P-8	0.002	206
P-9	0.023	166
P-10	-0.001	206
P-11	0.019	206

[1] Average length change of three each 76- by 152-mm (3- by 6-in.) cylinders.
[2] Negative value indicates shrinkage.
[3] Expansion in excess of 0.50 percent is considered failure.

Table 6
Results of Coefficient of Thermal Expansion Tests

Material	Coefficient of Expansion[1], Millionths/°C (Millionths/°F)
P-1	8.75 (4.86)
P-2	13.10 (7.28)
P-3	9.90 (5.50)
P-4	10.33 (5.74)
P-5	11.83 (6.57)
P-6	14.22 (7.90)
P-7	11.52 (6.40)
P-8	6.70 (3.72)
P-9	11.29 (6.27)
P-10	12.46 (6.92)
P-11	8.26 (4.59)

[1] Average of six each 51- by 102-mm (2- by 4-in.) cylinders.

Abrasion Resistance

The results of the underwater abrasion resistance tests are summarized in Table 7. Material P-5 was not tested because the quantity of material available was insufficient to fabricate the required test specimens. Plots of volume loss versus time for individual test specimens are shown in Figures 15 through 24. The two materials which exhibited the lowest volume losses during the tests, P-7 (EMACO S88-C) and P-8 (Pyrament-XT), also exhibited the highest compressive strengths. In fact, volume loss was generally inversely proportional to compressive strength (Figure 25). The results of tests on materials P-4 (Fibre Patch OV) and P-11 (Thoropatch) illustrate the effect of coarse aggregate on abrasion resistance. Although the two materials had similar compressive strengths, the volume loss of mortar material P-4 was three times higher than that of material P-11 with coarse aggregate.

Table 7
Results of Underwater Abrasion Resistance Tests

Material	Volume Loss[1], cu m
P-1	0.000471
P-2	0.001034
P-3	0.000279
P-4	0.001560
P-5	--
P-6	0.000623
P-7	0.000060
P-8	0.000123
P-9	0.000833
P-10	0.000547
P-11	0.000532

[1] Loss after 72 hr exposure.

Water Absorption

The results of the 10-min and 5-hr boiling water absorption tests are shown in Table 8. Four materials, P-3, 4, 5, and 9 (Structural Concrete VO, Fibre Patch OV, Octocrete, and Resist-A-Chem 7021 F), had 10-min absorptions exceeding 1 percent and 5-hr absorptions exceeding 10 percent. As might be expected, these materials also performed poorly in the freezing-and-thawing tests.

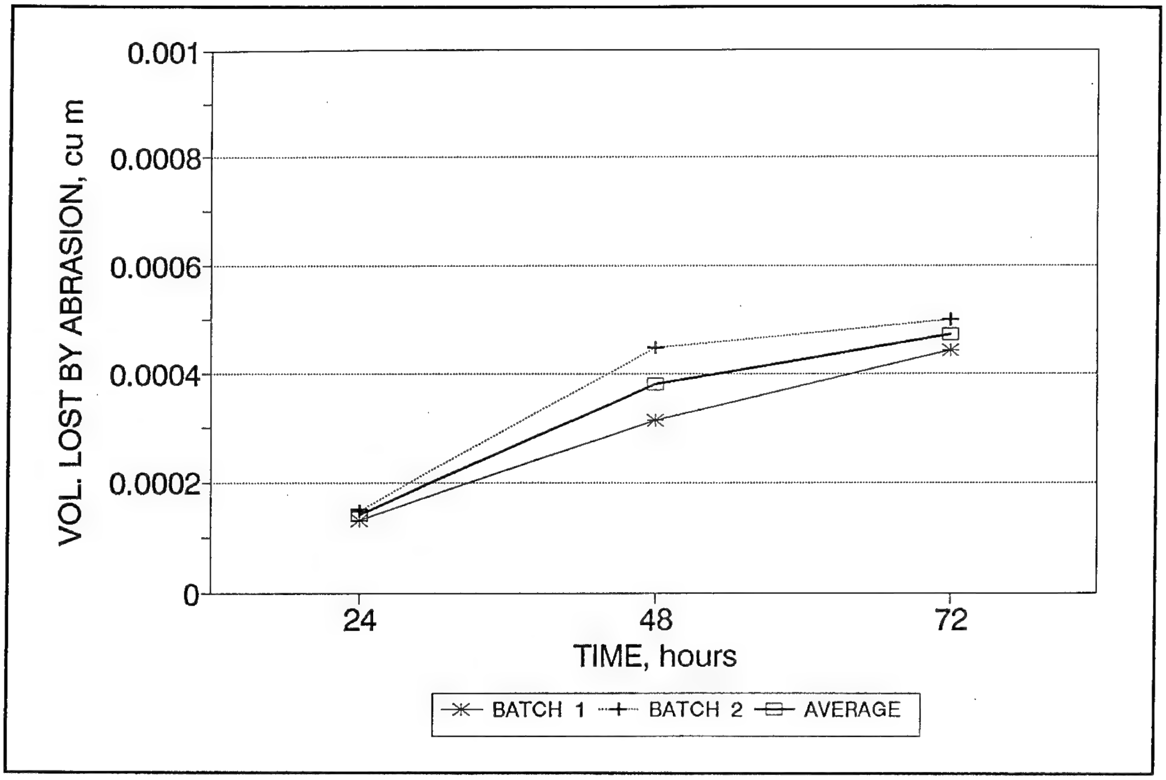

Figure 15. Results of abrasion resistance tests on material P-1

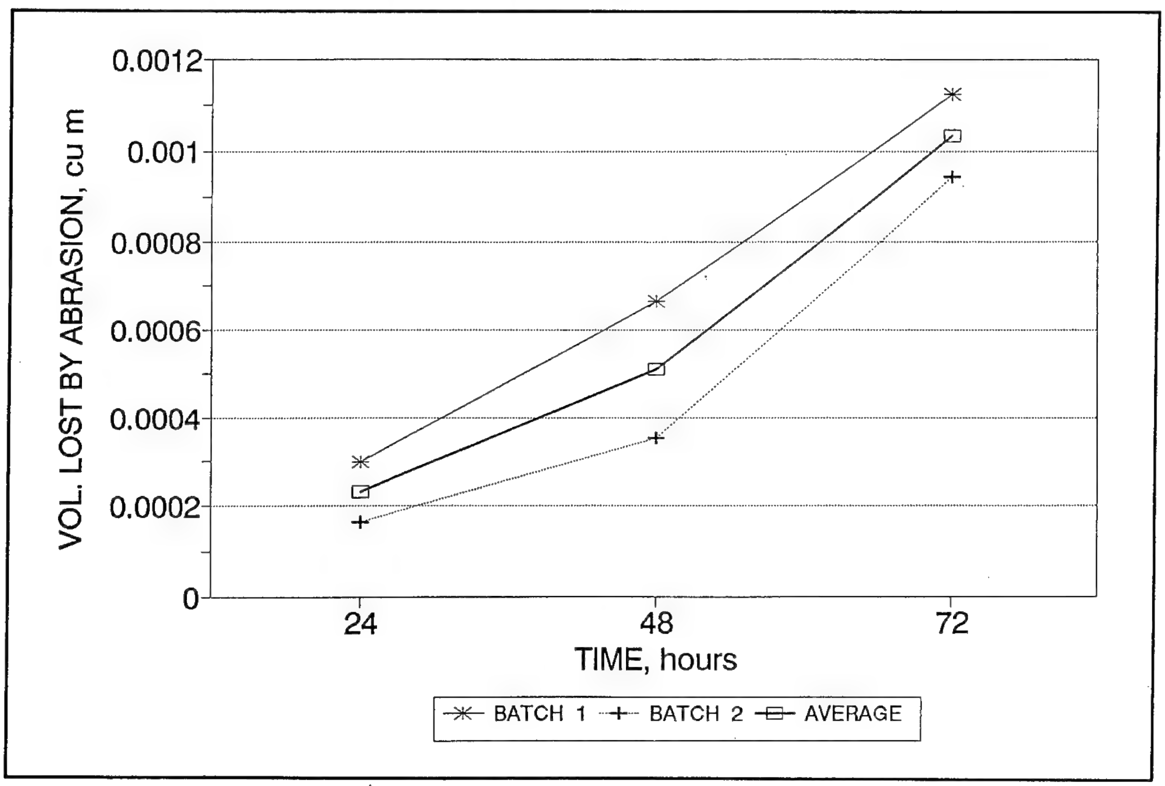

Figure 16. Results of abrasion resistance tests on material P-2

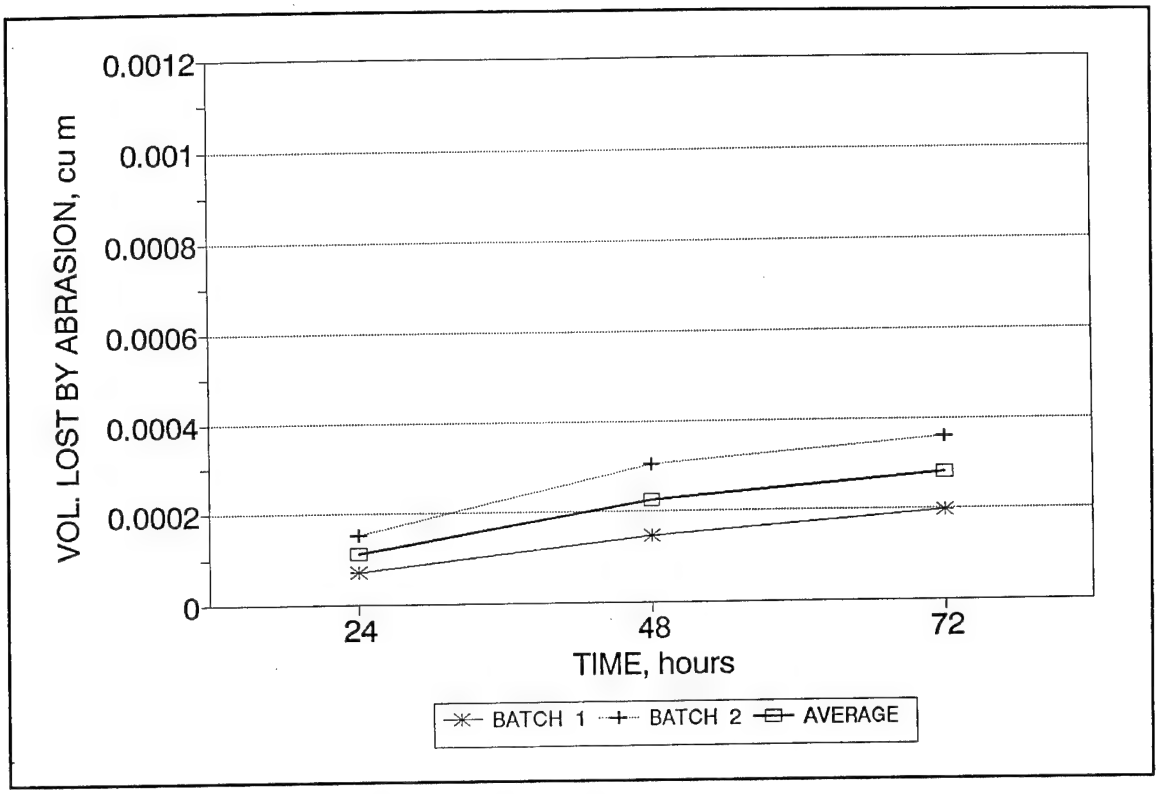

Figure 17. Results of abrasion resistance tests on material P-3

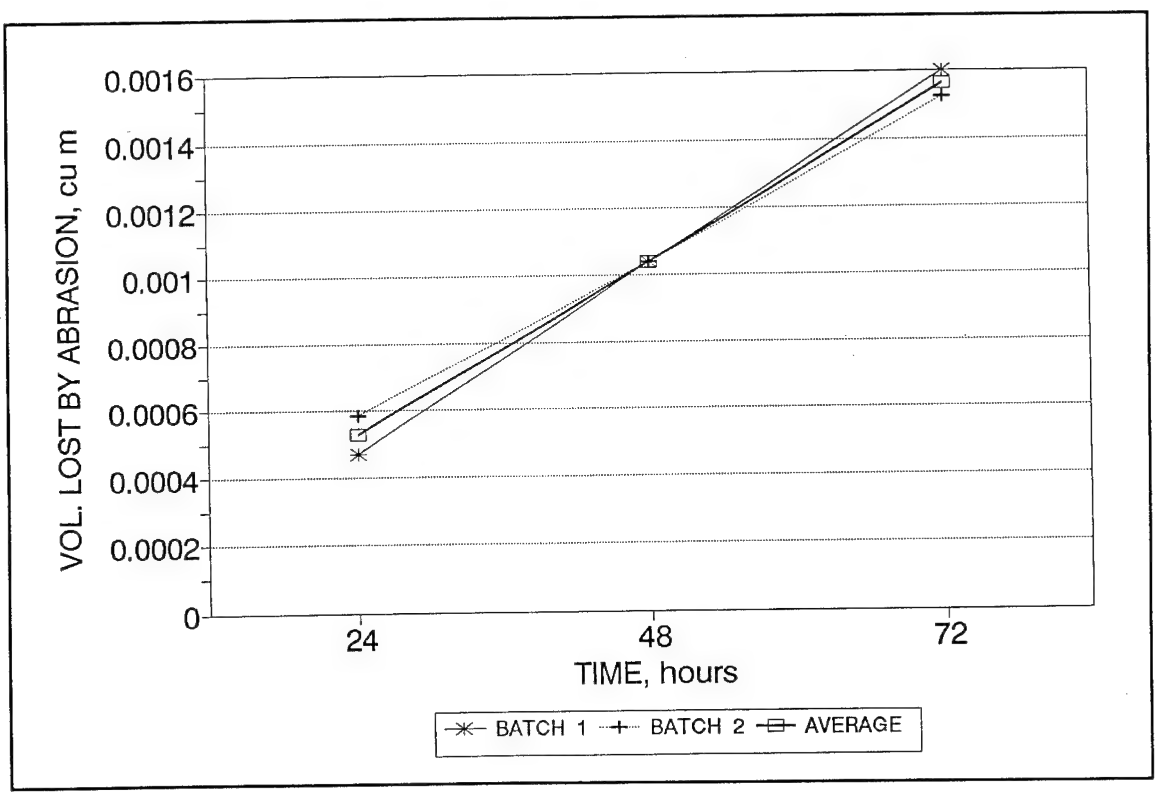

Figure 18. Results of abrasion resistance tests on material P-4

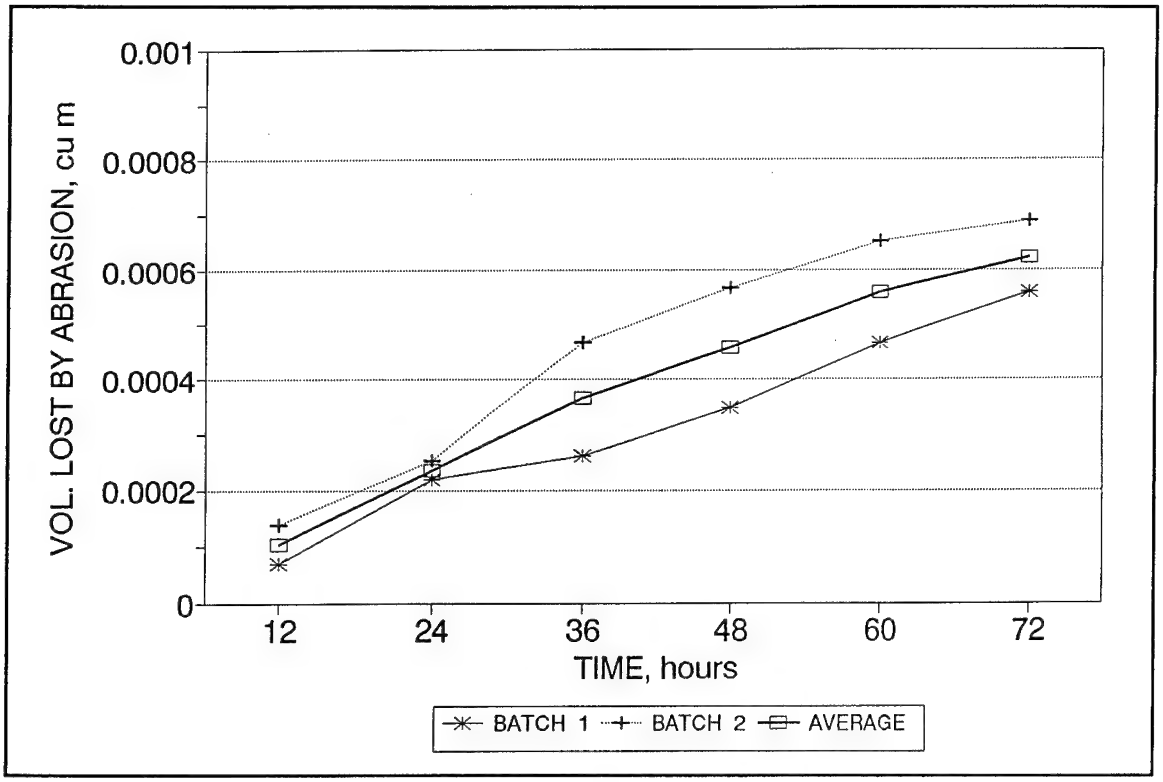

Figure 19. Results of abrasion resistance tests on material P-6

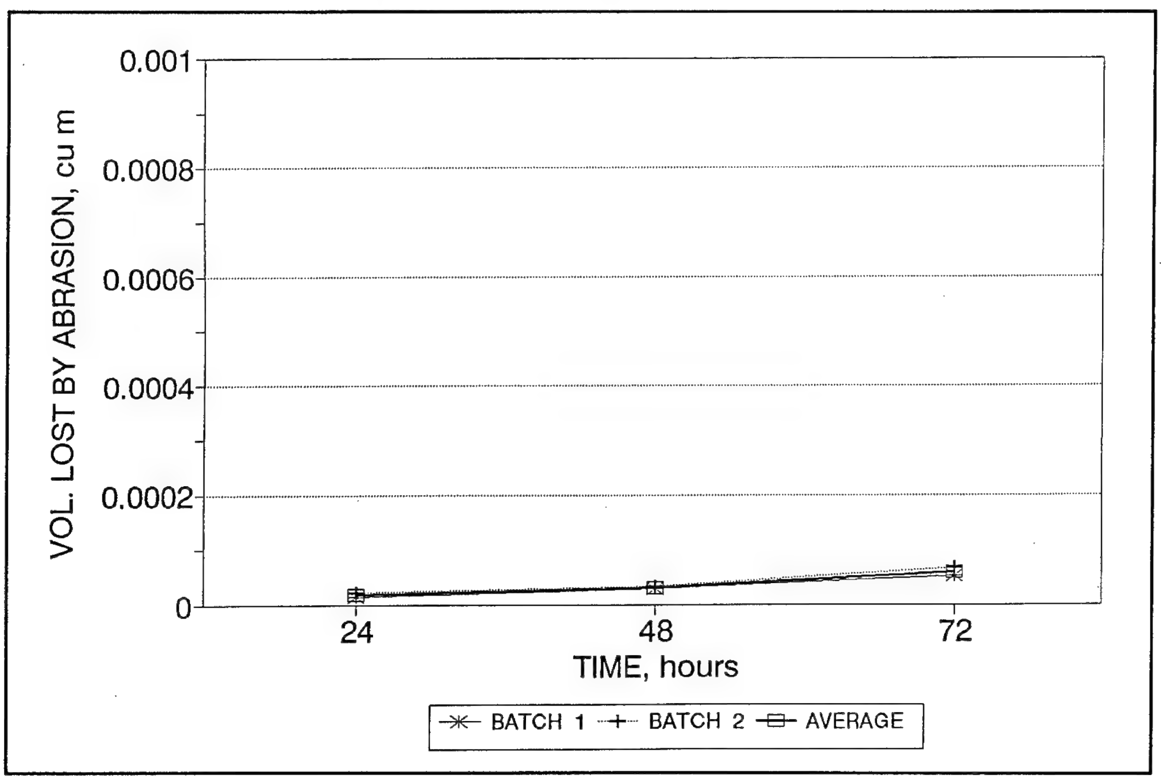

Figure 20. Results of abrasion resistance tests on material P-7

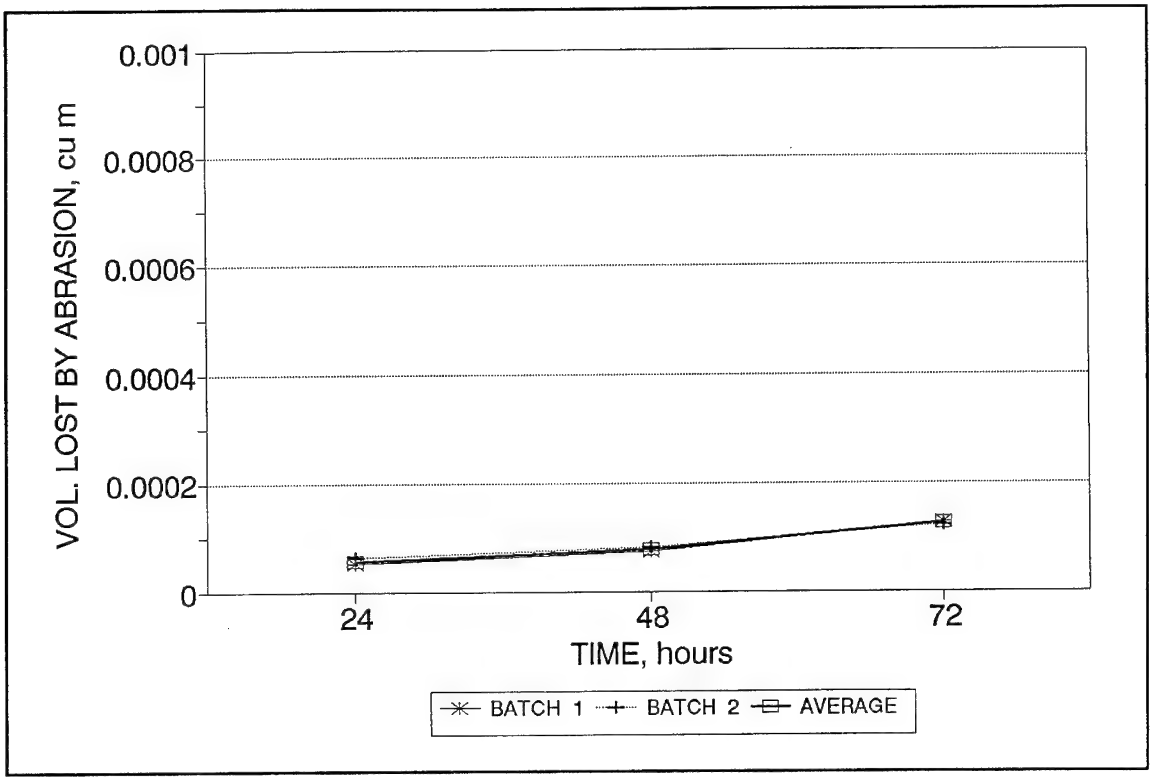

Figure 21. Results of abrasion resistance tests on material P-8

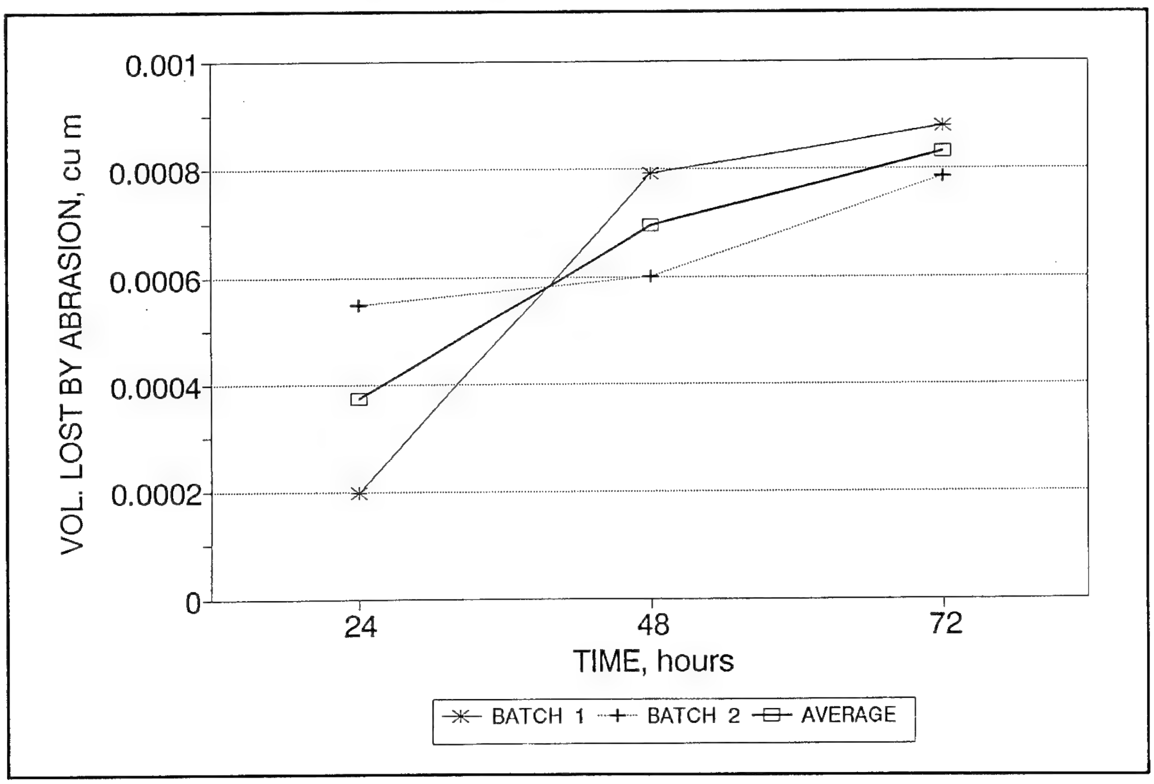

Figure 22. Results of abrasion resistance tests on material P-9

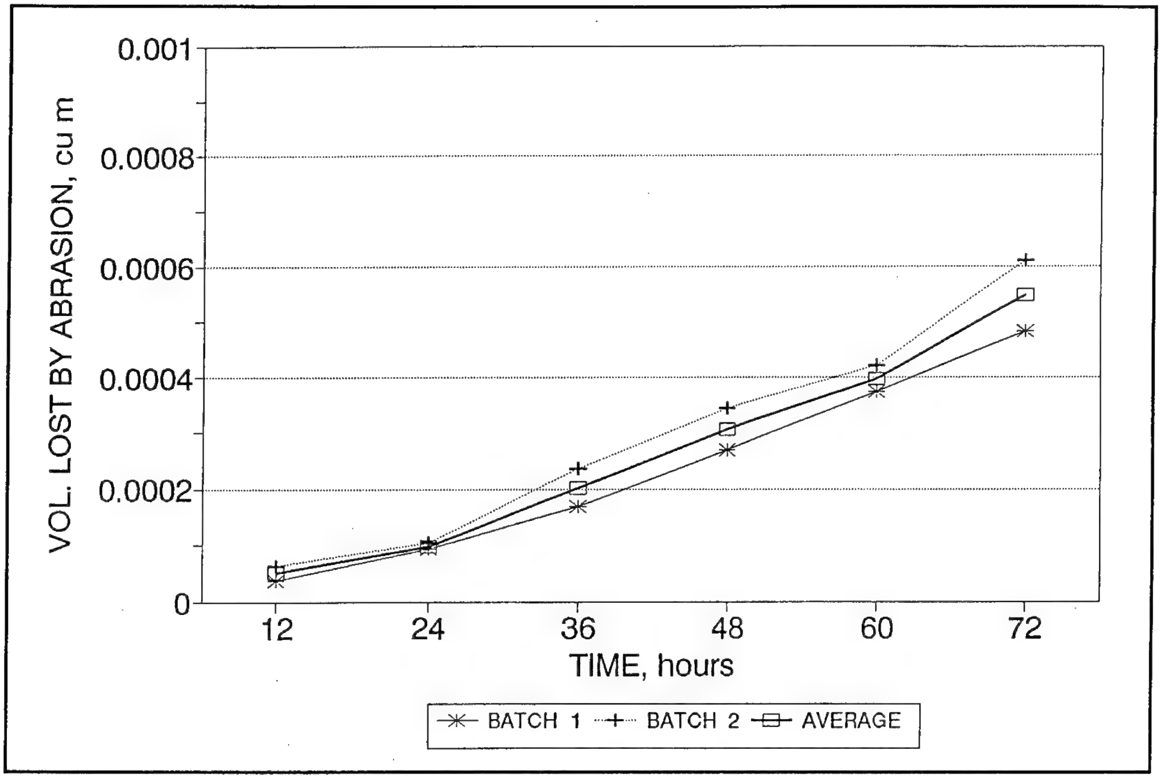

Figure 23. Results of abrasion resistance tests on material P-10

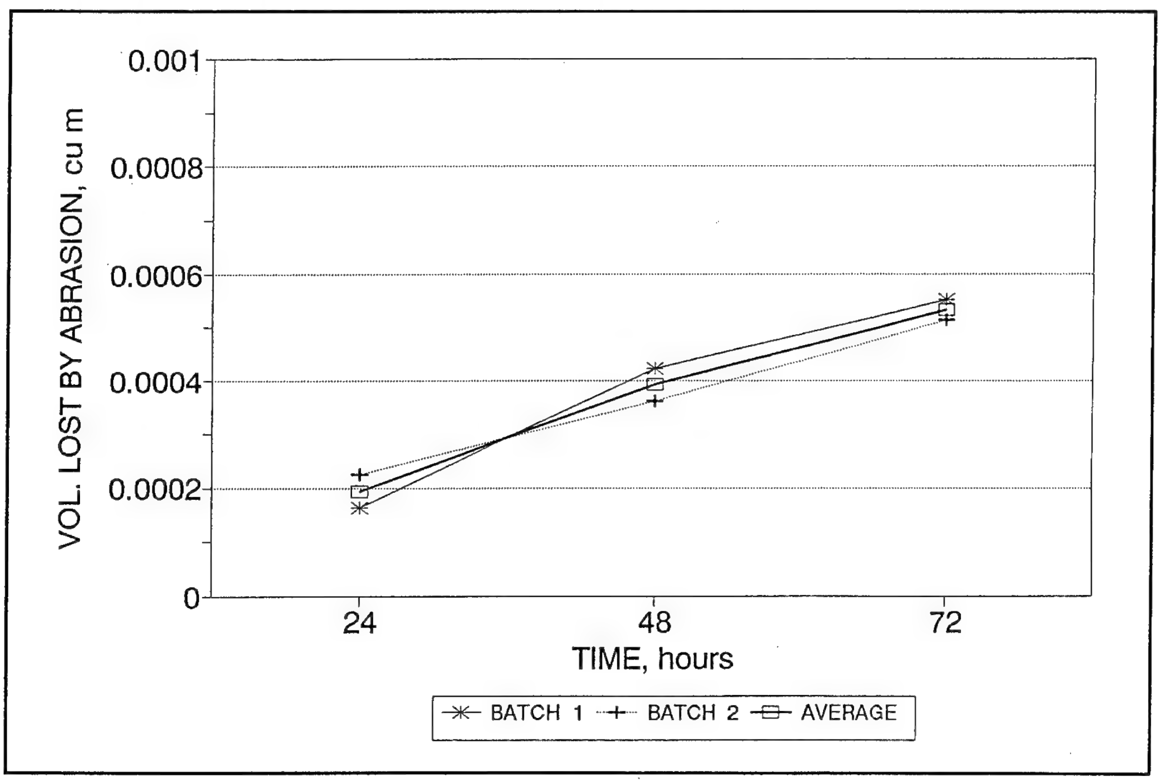

Figure 24. Results of abrasion resistance tests on material P-11

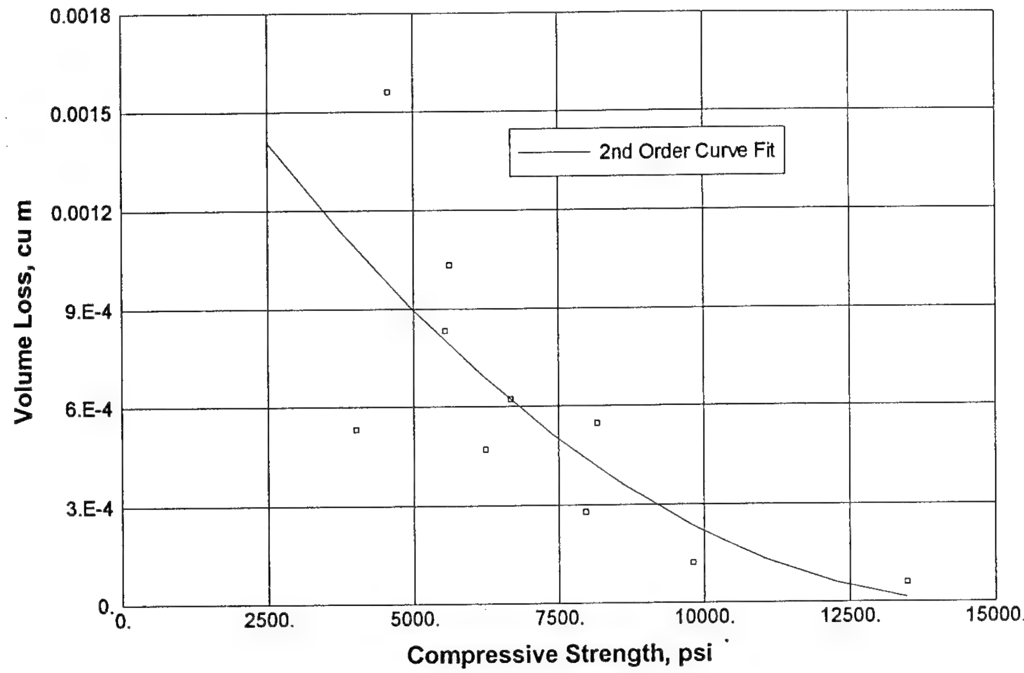

Figure 25. Relationship between abrasion resistance and compressive strength (Multiply pounds per square inch by 0.006894757 to obtain megapascals)

Table 8
Results of Water Absorption Tests

	Absorbed Water[1], % of Oven-Dry Mass	
Material	**10-min Boiling**	**5-hr Boiling**
P-1	0.34	2.01
P-2	0.62	7.96
P-3	1.84	16.27
P-4	2.21	16.29
P-5	3.60	13.51
P-6	0.67	5.63
P-7	2.33	7.39
P-8	1.60	5.37
P-9	6.18	13.09
P-10	0.93	3.23
P-11	1.65	13.82

[1] Average of two 76- by 152-mm (3- by 6-in.) cylinders.

Curing Shrinkage

Curing shrinkage is the expansion-contraction of the repair material beginning in the fresh, unhydrated state and extending for the period of time necessary for the material to approach stable conditions. This curing period includes the initial expansion, if any, because of the heat of hydration or the presence of expansive cements or additives and subsequent contraction as a result of cooling and moisture loss. The final results of the curing shrinkage tests are shown in Table 9. These terminal results, however, do not fully describe the entire expansion-contraction history of the curing shrinkage curve. If materials contain expansive cement or other expansive additives, the materials often expand initially and then harden in that expanded state. This hardening in a significantly expanded state can then be followed by cooling and moisture loss which reduces the extent of expansion and in some cases results in a net shrinkage. Considering only the final values of curing shrinkage may indicate that only a very small movement has occurred when in reality the total contraction from the expanded state to equilibrium can be significant.

Table 9
Results of Curing Shrinkage Tests

Material	Maximum Temperature, °C (°F) (Age, hr)	Shrinkage, Millionths (Age, hr)
P-1	No increase	3,400 (145)
P-2	28.1 (82.5) (13.5)	-230[1] (260)
P-3	50.0 (122.0) (2.3)	880 (258)
P-4	32.9 (91.3) (12.5)	-90 (426)
P-5	41.8 (107.3) (5.8)	320 (185)
P-6	26.7 (80.1) (17.4)	-480 (309)
P-7	42.4 (108.3) (10.2)	-480 (260)
P-8	30.3 (86.6) (1.9)	-80 (147)
P-9	28.7 (83.7) (12.5)	490 (430)
P-10	28.9 (84.0) (15.6)	40 (303)
P-11	23.7 (74.7) (29.6)	580 (189)

[1] Negative indicates expansion.

The plots of curing shrinkage versus time are shown in Figures 26 through 35. No plot of curing shrinkage for material P-7 is shown because this set of data was inadvertently erased from the computer following completion of the test. Only the final value of curing shrinkage, which was manually recorded, is available for this material.

Drying Shrinkage

In the initial drying shrinkage tests, specimens from each of the repair materials were monitored for 28 days. Subsequently, the drying shrinkage tests were repeated for five of the materials (P-4, 6, 7, 9, and 10), and the duration of strain measurements was extended to approximately 60 days. The values for 28-day drying shrinkage shown in Table 10 are the average result in those cases where two tests were made. The 28-day test results were similar when comparing the two runs, except for material P-4 where the average shrinkage for the two runs was 1,850 and 1,400 millionths. Overall, drying shrinkage strains at 28 days ranged from 460 to 3,370 millionths. Material P-5 (Octocrete) exhibited the highest drying shrinkage. In comparison, the next highest value was about one-half that of material P-5. As might be expected, the lowest values of drying shrinkage were associated with the three materials containing coarse aggregate that were evaluated with a larger test specimen. The 28-day drying shrinkage values for these materials, P-1, 8, and 11 (BASF ND-614, Pyrament-XT, and Thoropatch) were all within the range of 460 to 490 millionths. However, these shrinkage values were only slightly lower than those of the mortar materials P-2 and P-6 (Fosroc DN-74 and EMACO R300) which were 510 and 590 millionths, respectively. Typically, conventional concrete exhibits a drying shrinkage of about 500 millionths.

The plots of drying shrinkage versus time for those five materials with extended strain measurements are shown in Figure 36. All of the five materials tested for longer than 28 days showed additional shrinkage after 28 days. Material P-6 (EMACO R300) had the highest increase in shrinkage (310 millionths) between 28 and 60 days of the five materials tested for this length of time. Based on this limited amount of testing, additional measurements after 28 days may be necessary to adequately evaluate shrinkage properties of repair materials. Additional data on drying shrinkage were obtained from the unloaded control cylinders in the creep tests described in the following.

Creep

A sustained compressive load of 5.5 MPa (800 psi) was applied to the creep specimens at 28 days. Elastic strains were measured following application of the loads and strains were measured periodically during the loading period. Strain measurements were also made on unloaded control cylinders during this period. In each case, specimens were maintained at 50 percent relative humidity

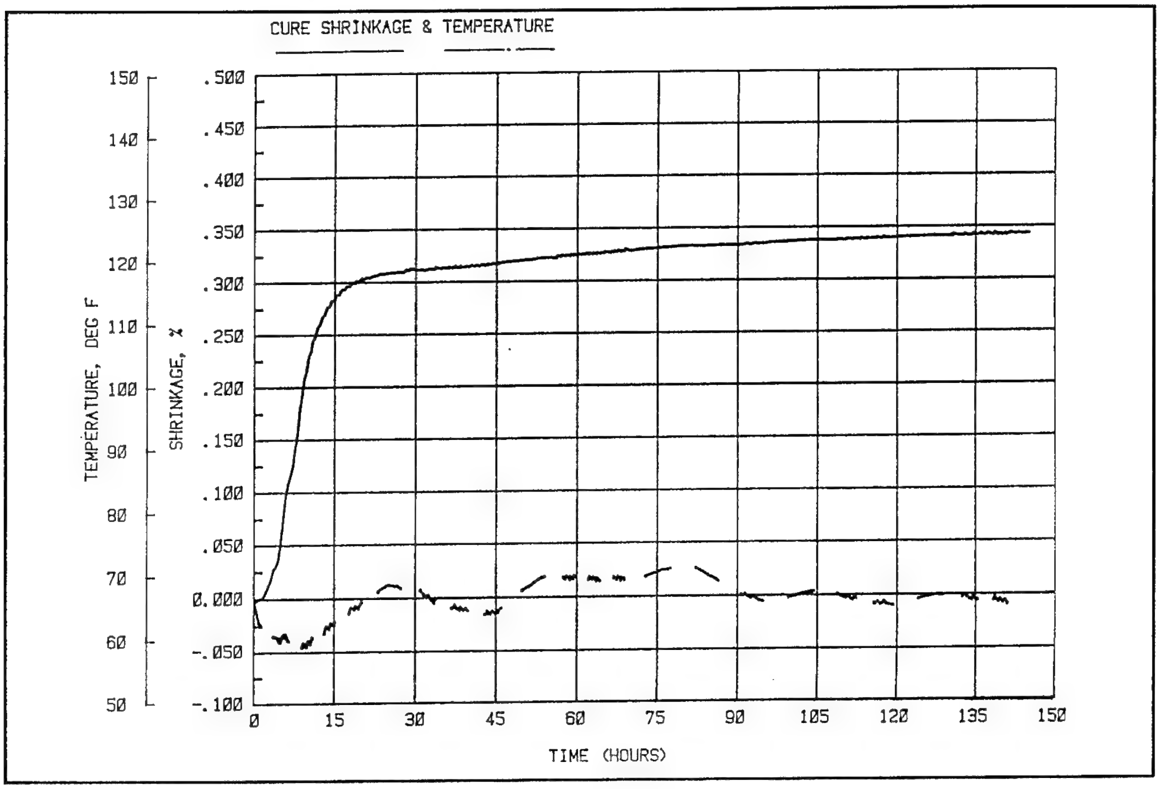

Figure 26. Results of curing shrinkage tests on material P-1 (°C = (5/9)(°F - 32))

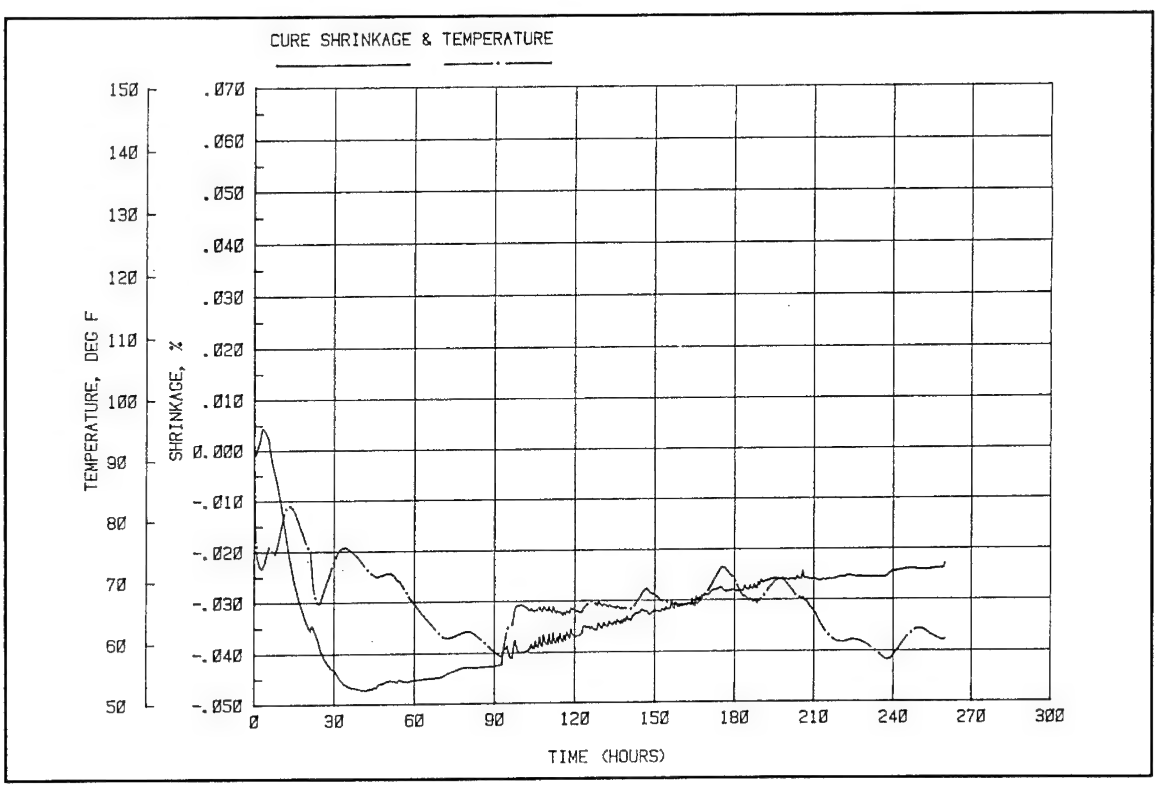

Figure 27. Results of curing shrinkage tests on material P-2 (°C = (5/9)(°F - 32))

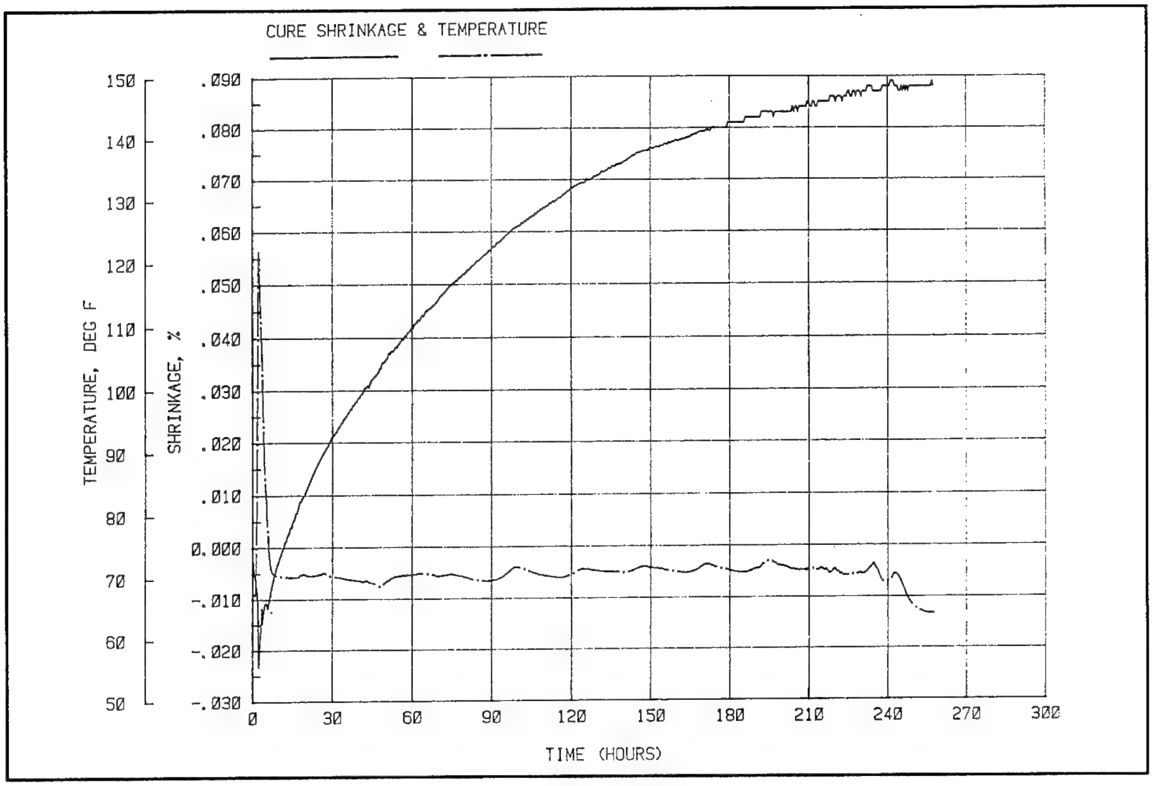

Figure 28. Results of curing shrinkage tests on material P-3 (°C = (5/9)(°F - 32))

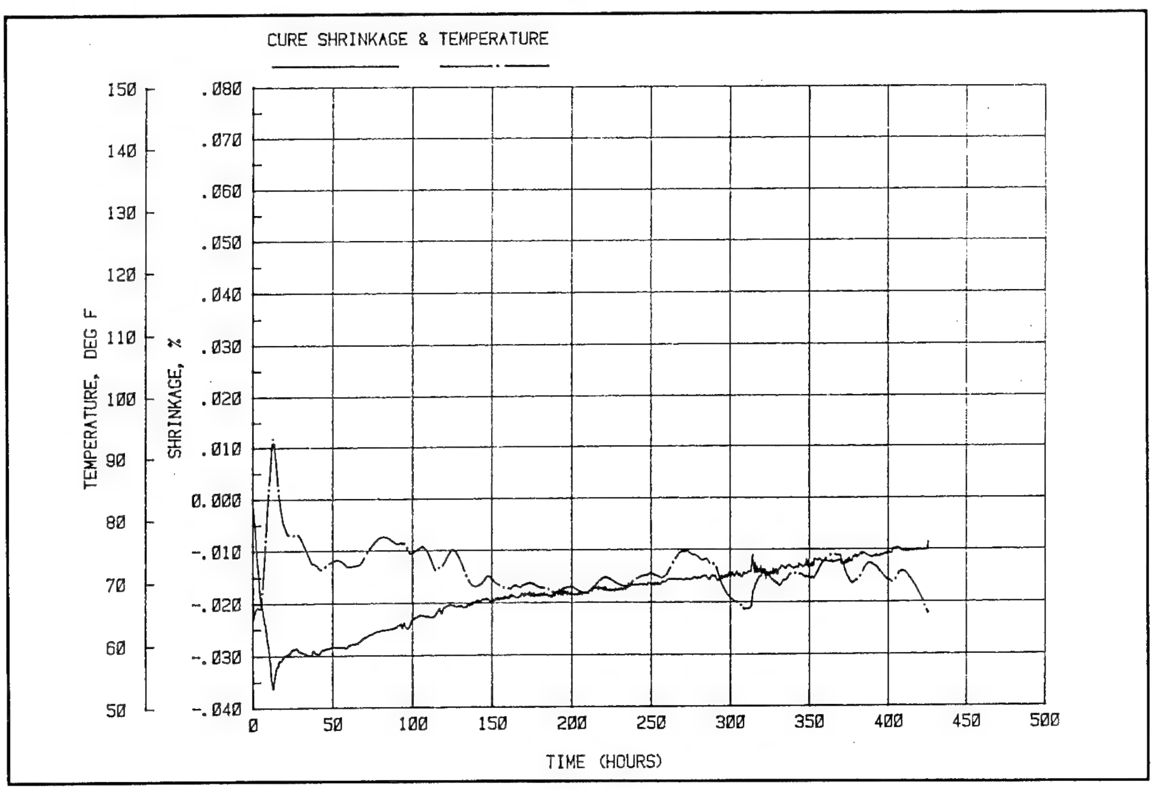

Figure 29. Results of curing shrinkage tests on material P-4 (°C = (5/9)(°F - 32))

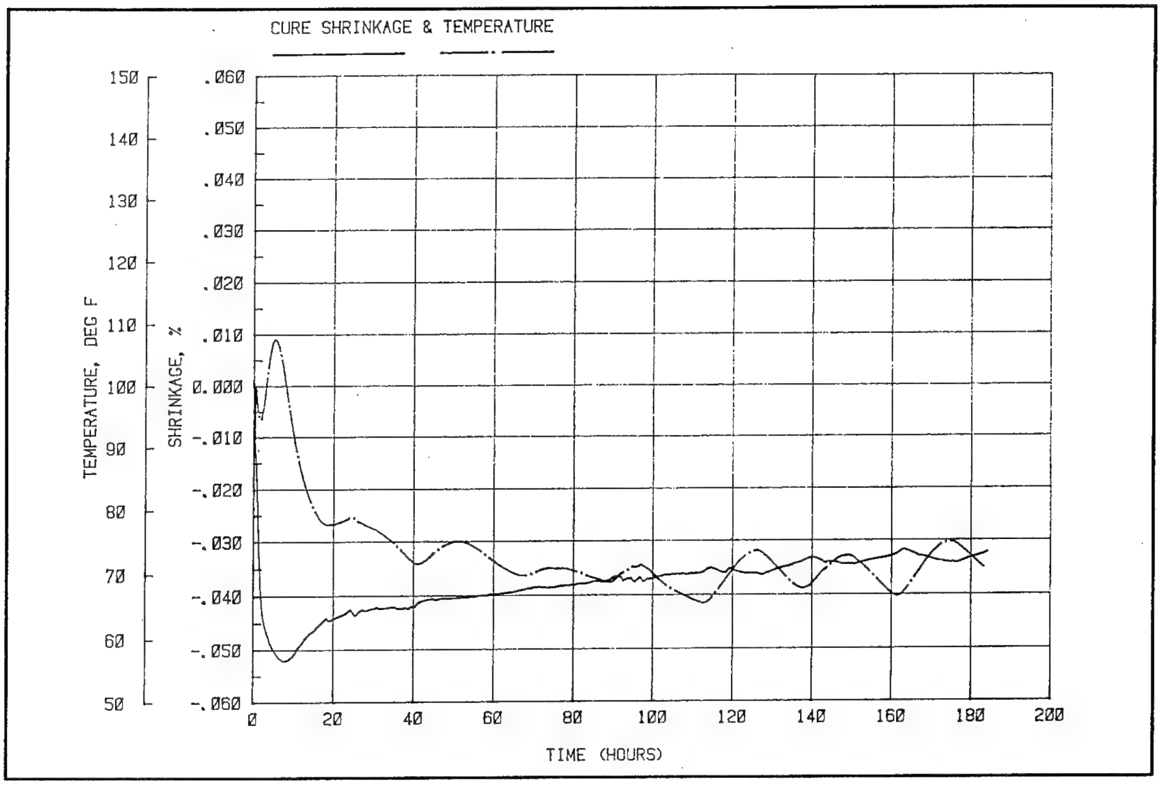

Figure 30. Results of curing shrinkage tests on material P-5 (°C = (5/9)(°F - 32))

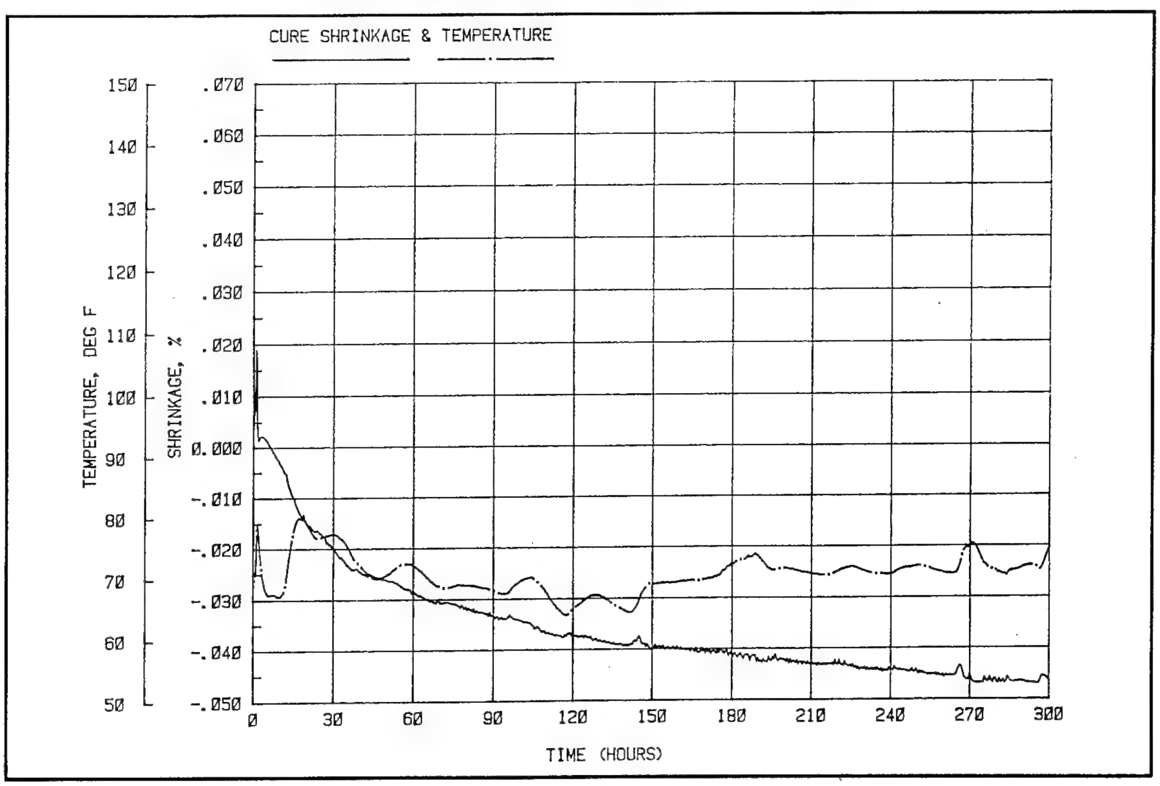

Figure 31. Results of curing shrinkage tests on material P-6 (°C = (5/9)(°F - 32))

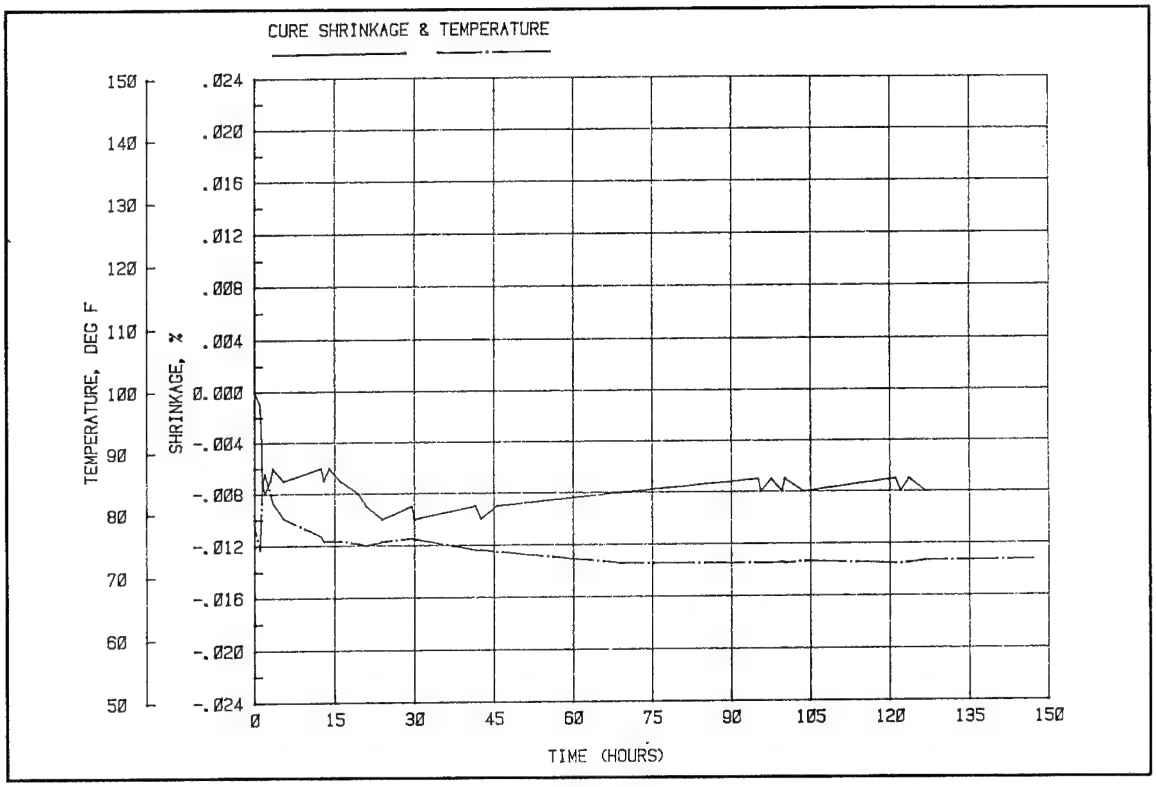

Figure 32. Results of curing shrinkage tests on material P-8 (°C = (5/9)(°F - 32))

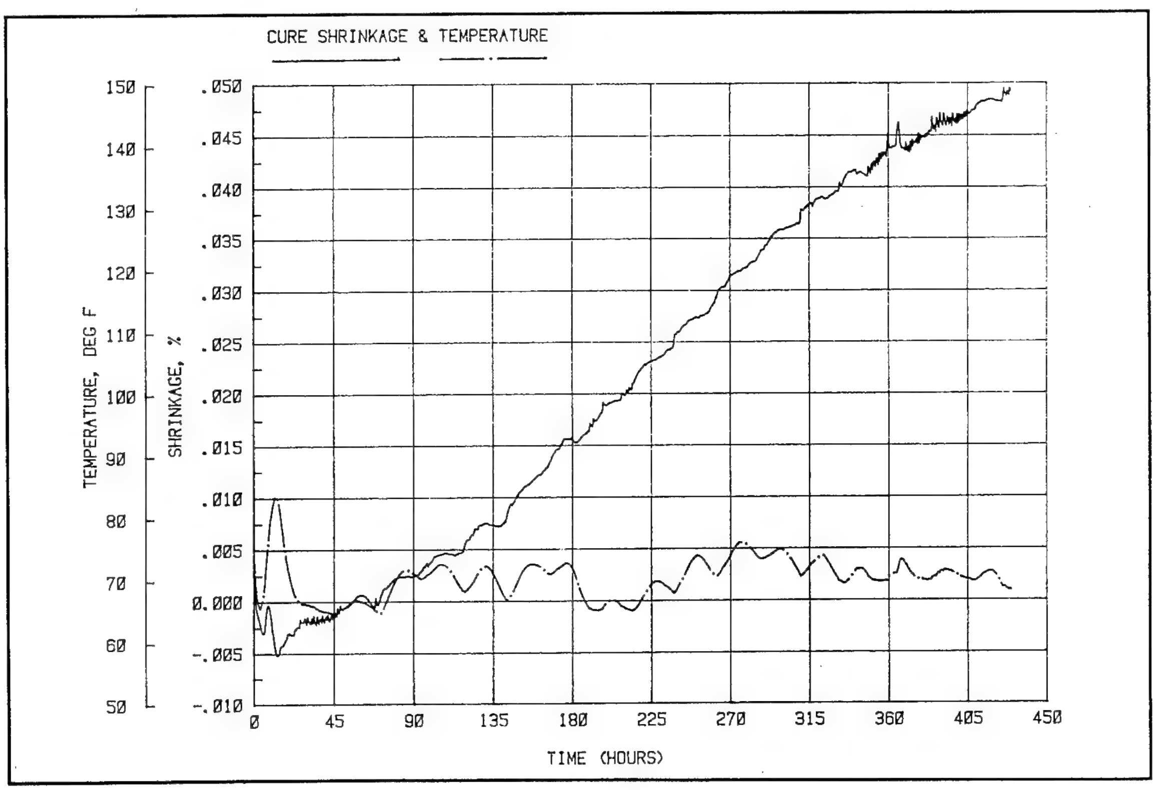

Figure 33. Results of curing shrinkage tests on material P-9 (°C = (5/9)(°F - 32))

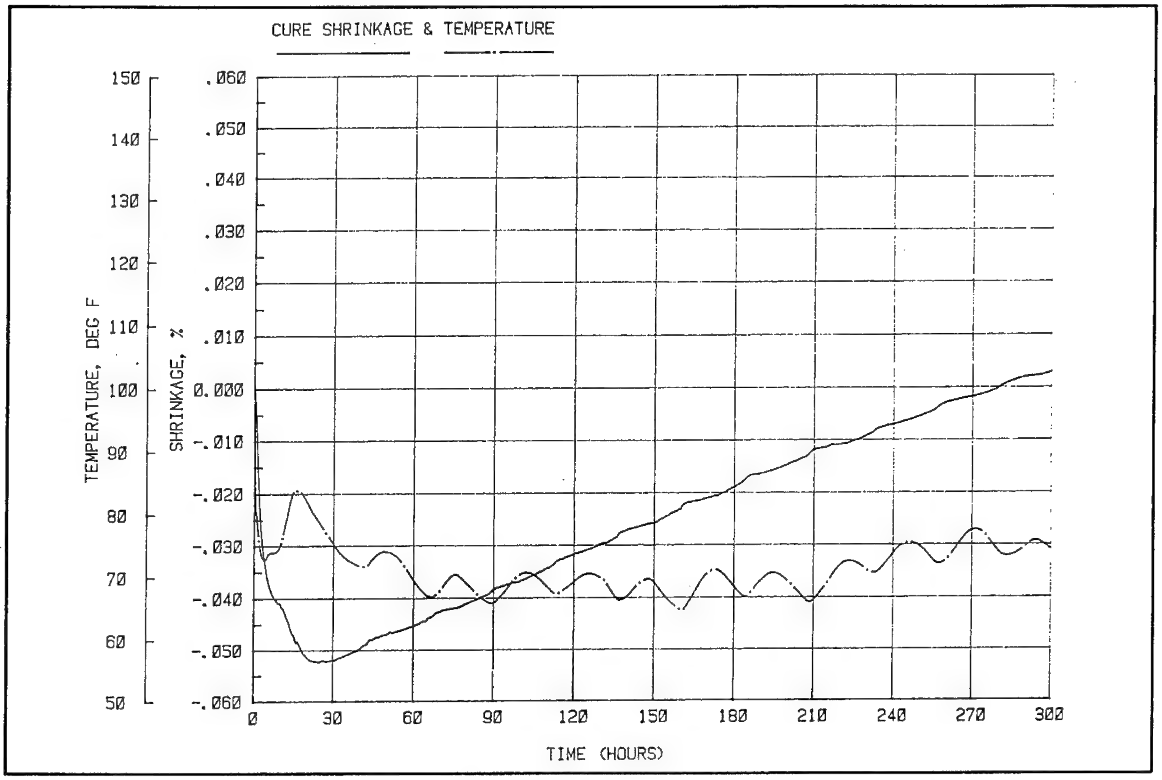

Figure 34. Results of curing shrinkage tests on material P-10 (°C = (5/9)(°F - 32))

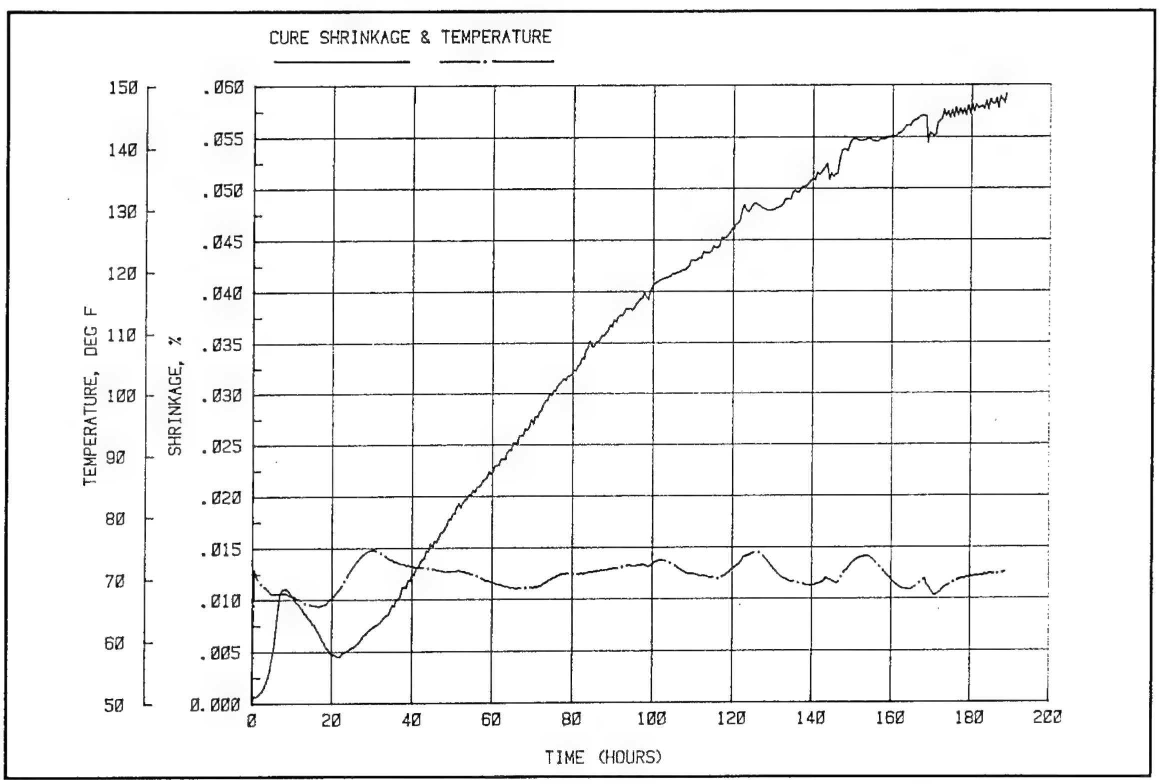

Figure 35. Results of curing shrinkage tests on material P-11 (°C = (5/9)(°F - 32))

Table 10
Results of Drying Shrinkage Tests

Material	28-day Shrinkage[1], Millionths
P-1	470[2]
P-2	510
P-3	810
P-4	1,620
P-5	3,370
P-6	590
P-7	1,080
P-8	460[2]
P-9	870
P-10	1,280
P-11	490[2]

[1] Average of four 25- by 25- by 286-mm (1- by 1- by 11-1/4-in.) beams unless otherwise noted.
[2] Average of four 76- by 76- by 286-mm (3- by 3- by 11-1/4-in.) beams.

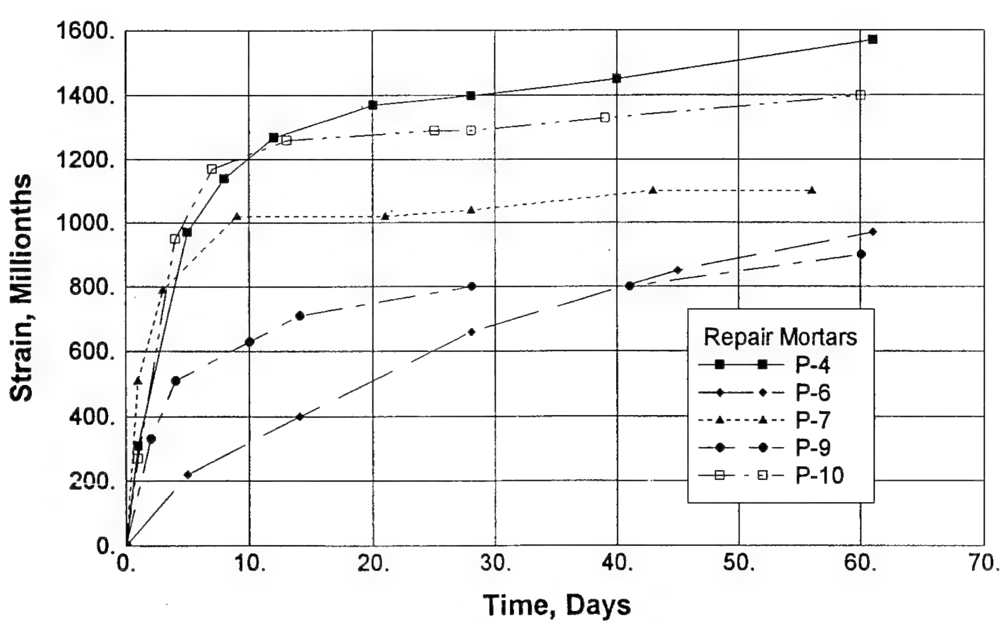

Figure 36. Drying shrinkage versus time for selected repair mortars

and 23 °C (73.4 °F). Results of the strain measurements are shown in Figures 37 through 47.

Compressive creep strains were calculated by subtracting the elastic strain from the total strain and correcting this value for the drying shrinkage exhibited by the control specimens. Specific creep strains for each material were calculated by dividing the creep strains by the applied load of 5.5 MPa (800 psi). A curve-of-best fit was then calculated for the specific creep strains (Figures 48 through 51). The equations for these curves were used to calculate the specific creep at 1 yr for comparison purposes (Table 11). On this basis, creep strains ranged from 32.34 to 422.64 millionths/MPa (0.223 to 2.914 millionths/psi) for materials P-7 (EMACO S88-C) and P-5 (Octocrete), respectively.

The unloaded control cylinders generally exhibited continuing drying shrinkage throughout the monitoring period. Shrinkage strains at the end of the approximately 600-day period are compared to short-term results in Table 12. With one exception, the 28-day drying shrinkage determined by measurements on small beams was higher than the shrinkage exhibited by 152- by 305-mm (6- by 12-in.) cylinders after approximately 600 days of drying. Results of the long-term shrinkage tests ranged from 337 to 2,387 millionths for materials P-11 (Thoropatch) and P-5 (Octocrete), respectively. Typically, conventional concrete under similar conditions will exhibit a drying shrinkage of about 300 millionths.

Rapid Chloride Permeability

The results of the rapid chloride permeability tests are shown in Table 13. The chloride permeability of the materials was rated in accordance with guidance given in the test method. On this basis, material P-10 (Power Elite Gel Patch) exhibited negligible chloride permeability and three other materials, P-3, P-6, and P-7 (Structural Concrete V/O, EMACO R300, and EMACO S88-C) exhibited very low chloride permeability.

Water-Vapor Transmission

The results of the water-vapor transmission tests (WVT) are shown in Table 14. Results ranged from 5.50 to 43.41 $g/m^2/24$ hr for materials P-10 (Power Elite Gel Patch) and P-5 (Octocrete), respectively. This test was previously used by WES to determine the WVT of masonry mortars coated with sealers. The Type S masonry mortar control in these tests exhibited a WVT of 62.5 $g/m^2/24$ hr. All of the repair materials exhibited WVT values that were lower than this control.

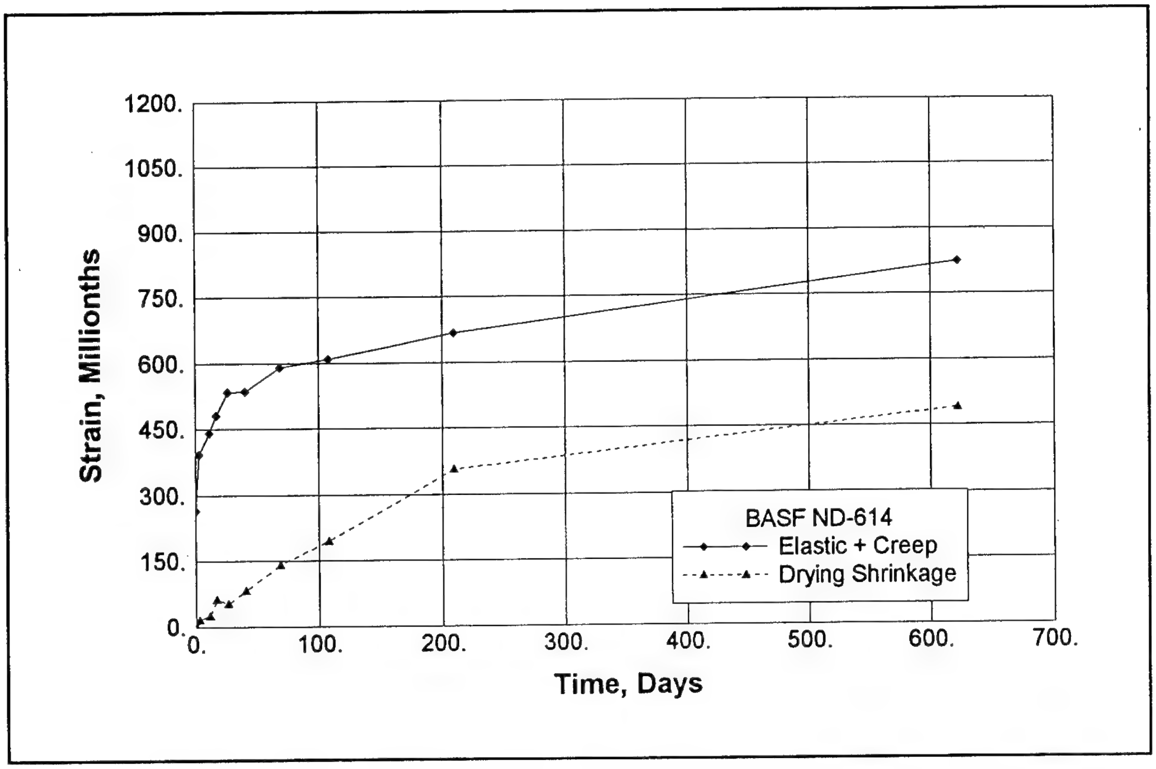

Figure 37. Results of strain measurements on creep and control specimens, material P-1

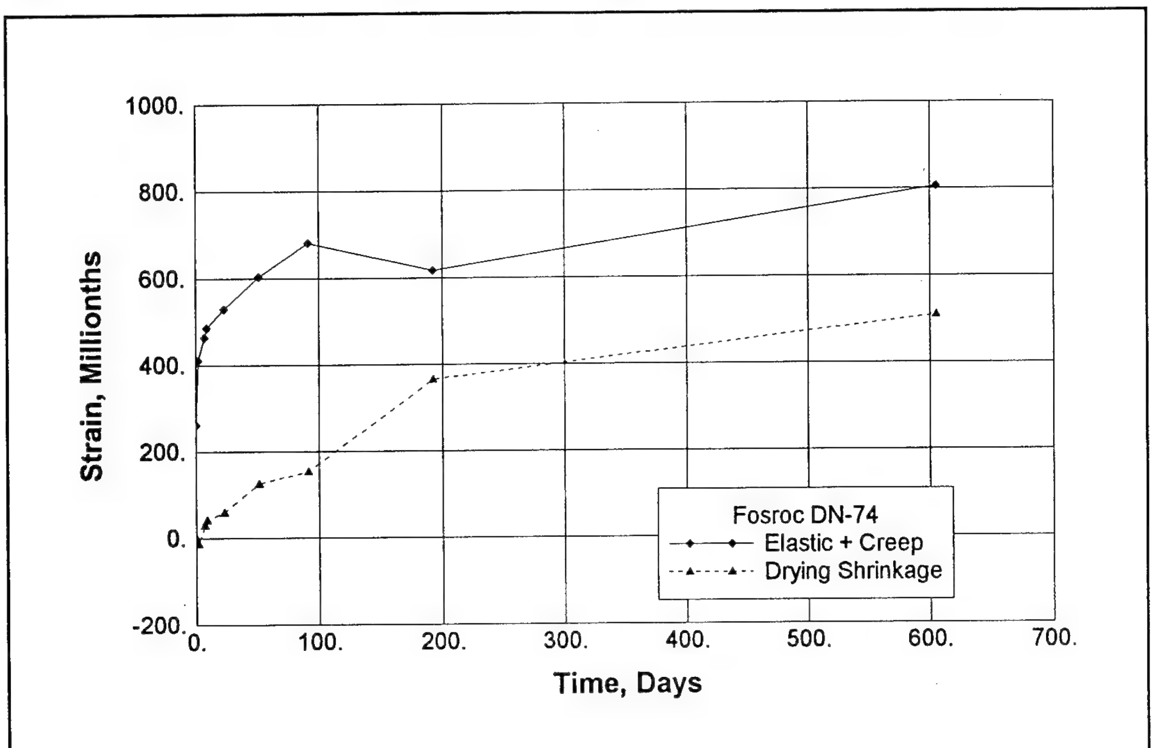

Figure 38. Results of strain measurements on creep and control specimens, material P-2

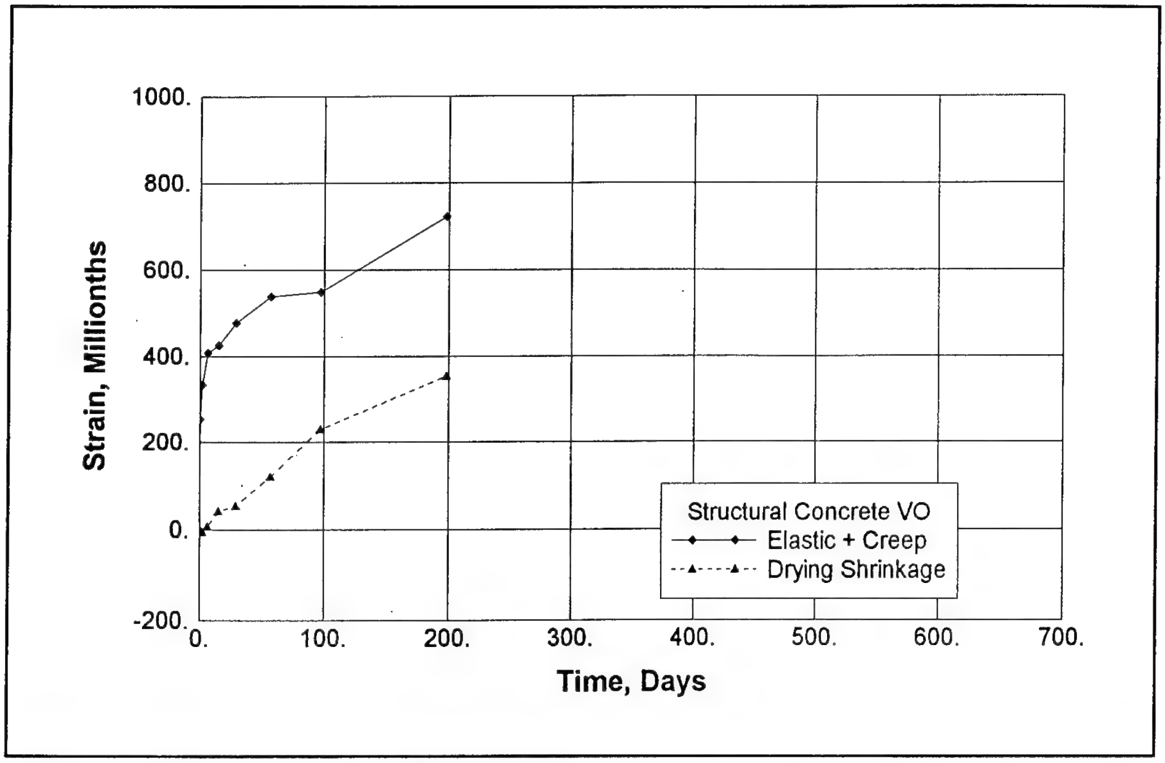

Figure 39. Results of strain measurements on creep and control specimens, material P-3

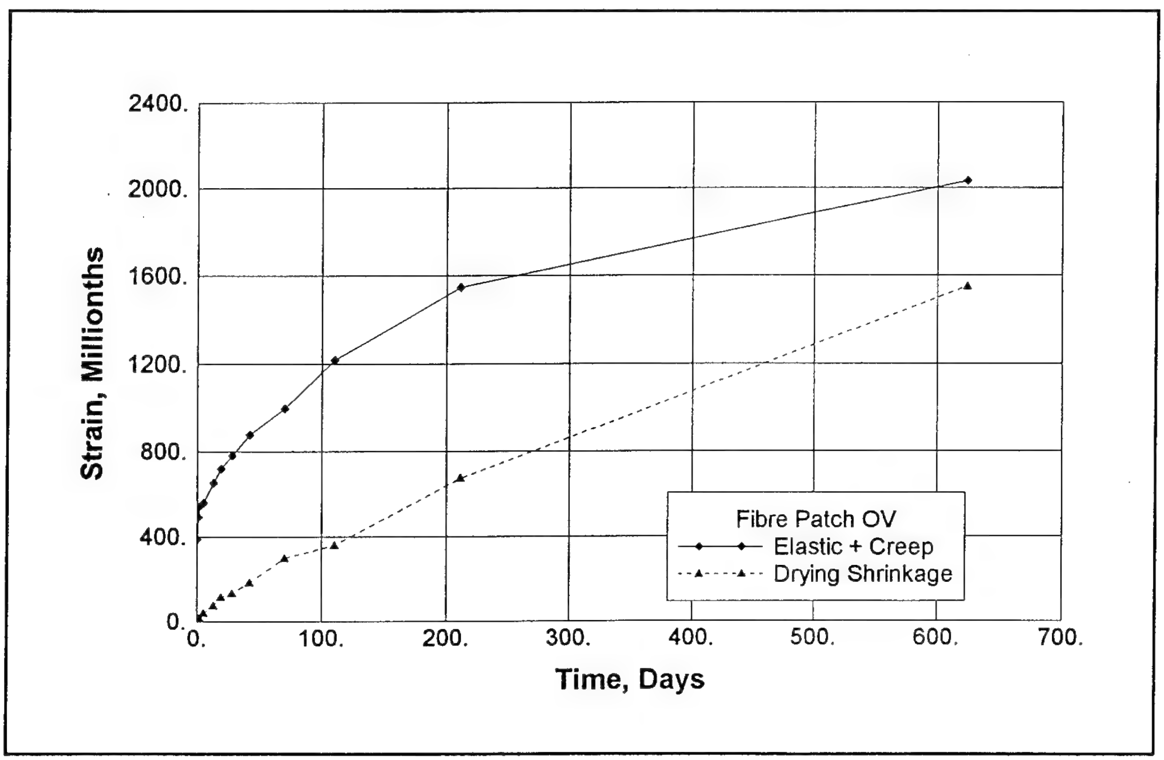

Figure 40. Results of strain measurements on creep and control specimens, material P-4

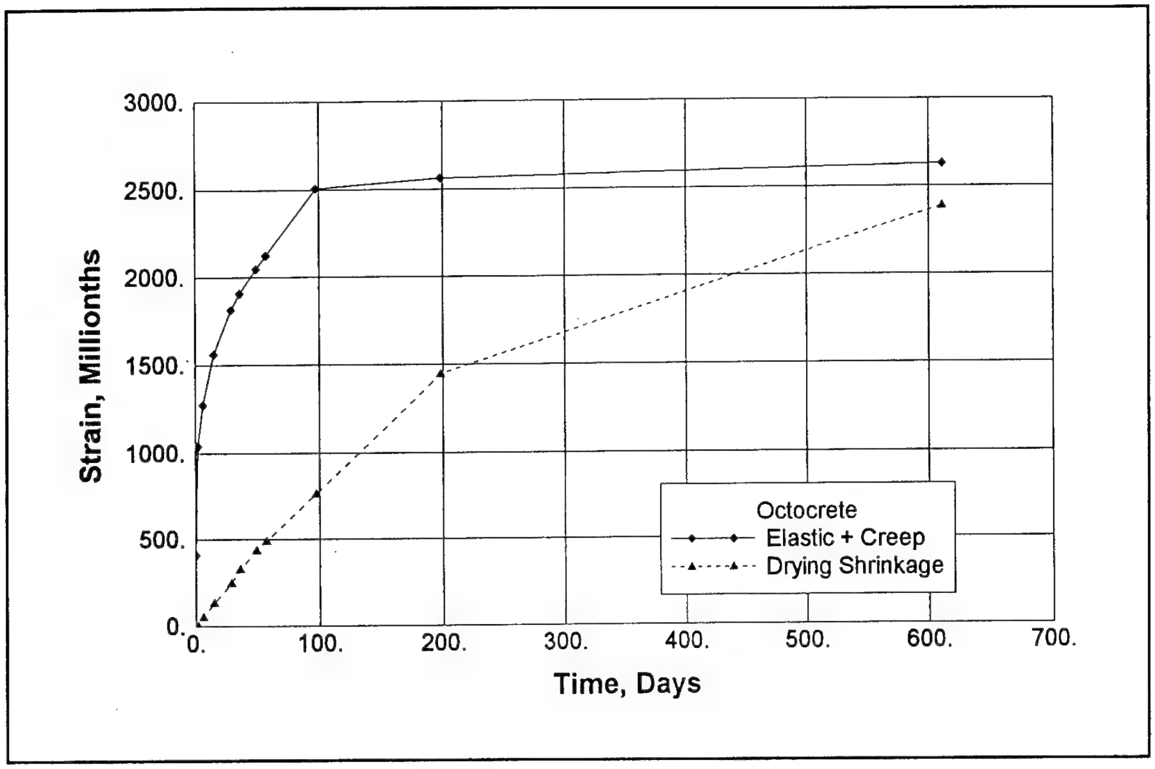

Figure 41. Results of strain measurements on creep and control specimens, material P-5

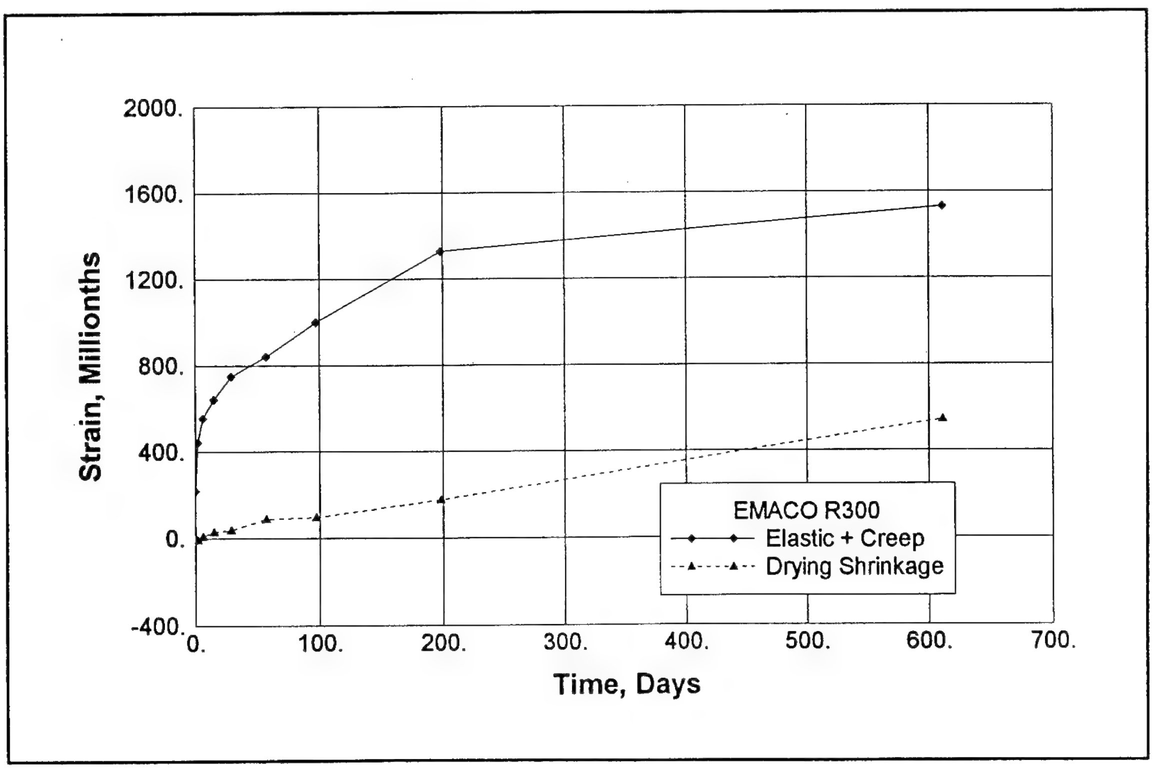

Figure 42. Results of strain measurements on creep and control specimens, material P-6

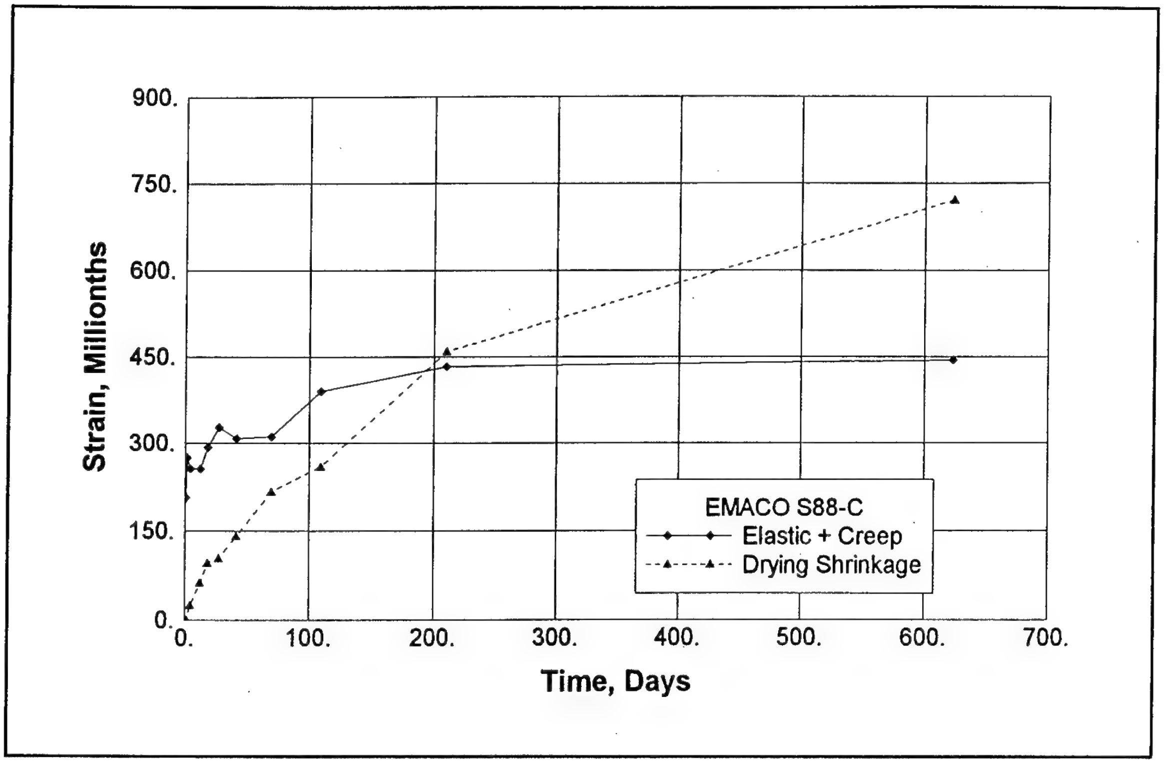

Figure 43. Results of strain measurements on creep and control specimens, material P-7

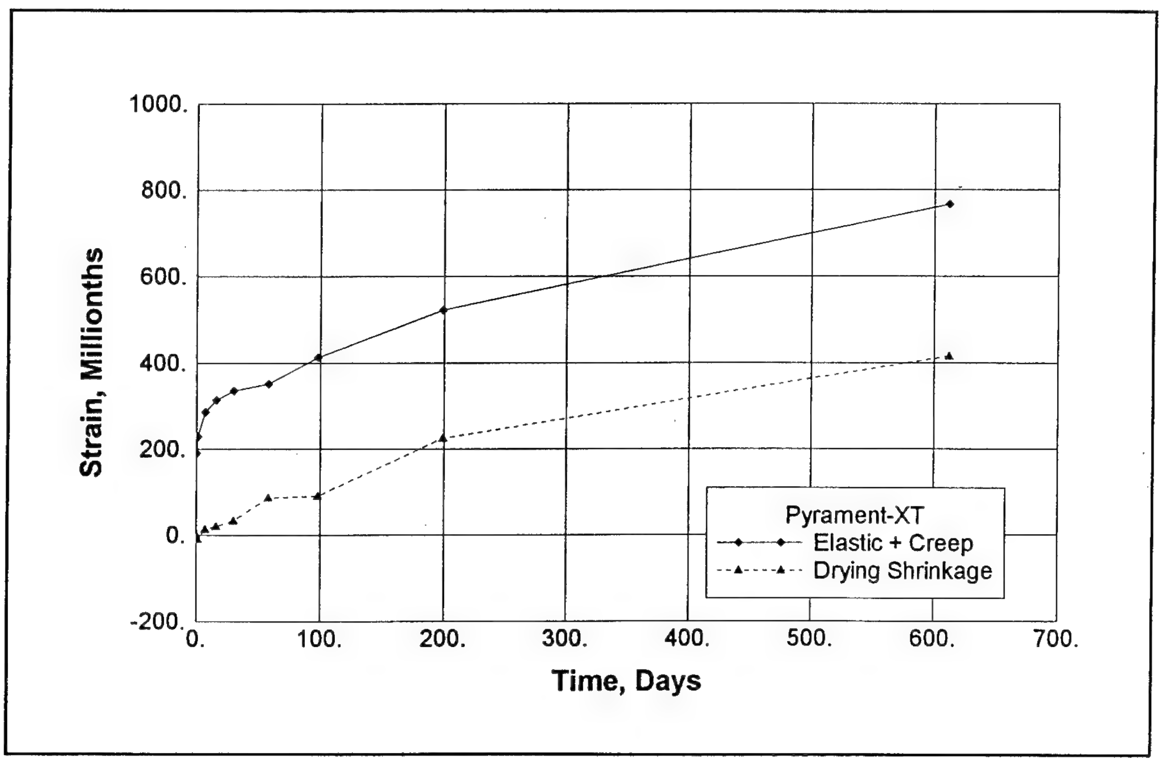

Figure 44. Results of strain measurements on creep and control specimens, material P-8

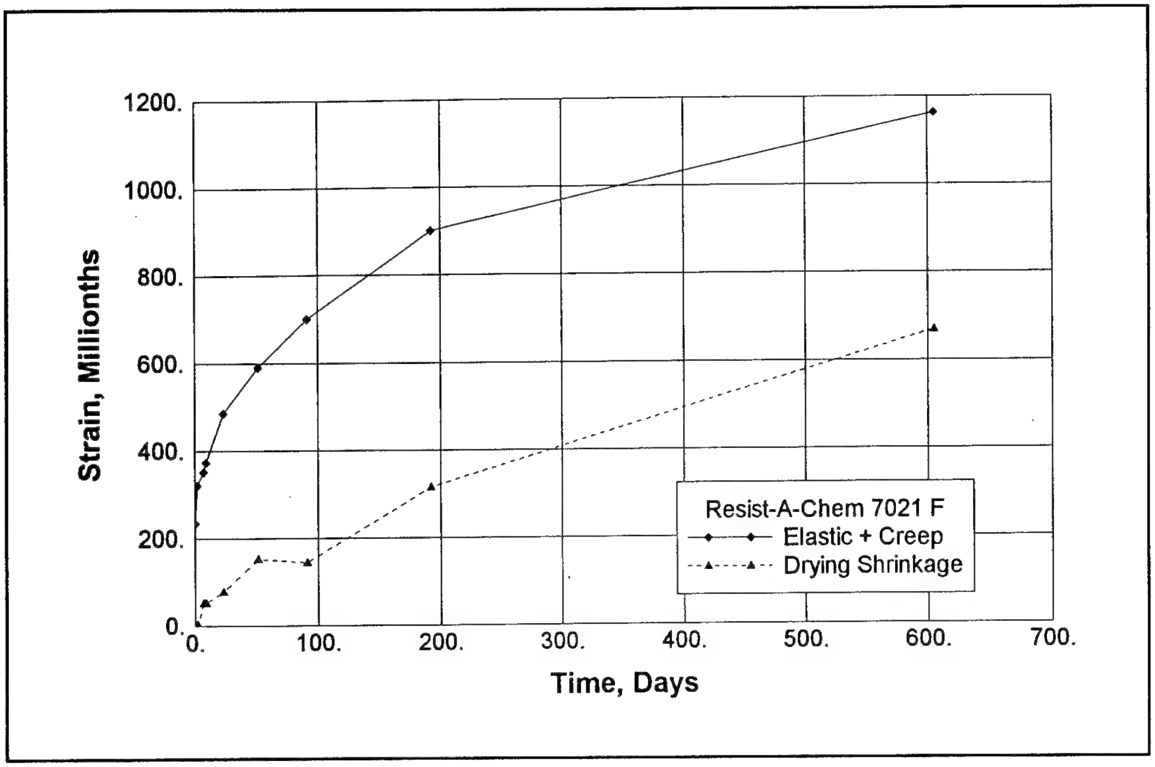

Figure 45. Results of strain measurements on creep and control specimens, material P-9

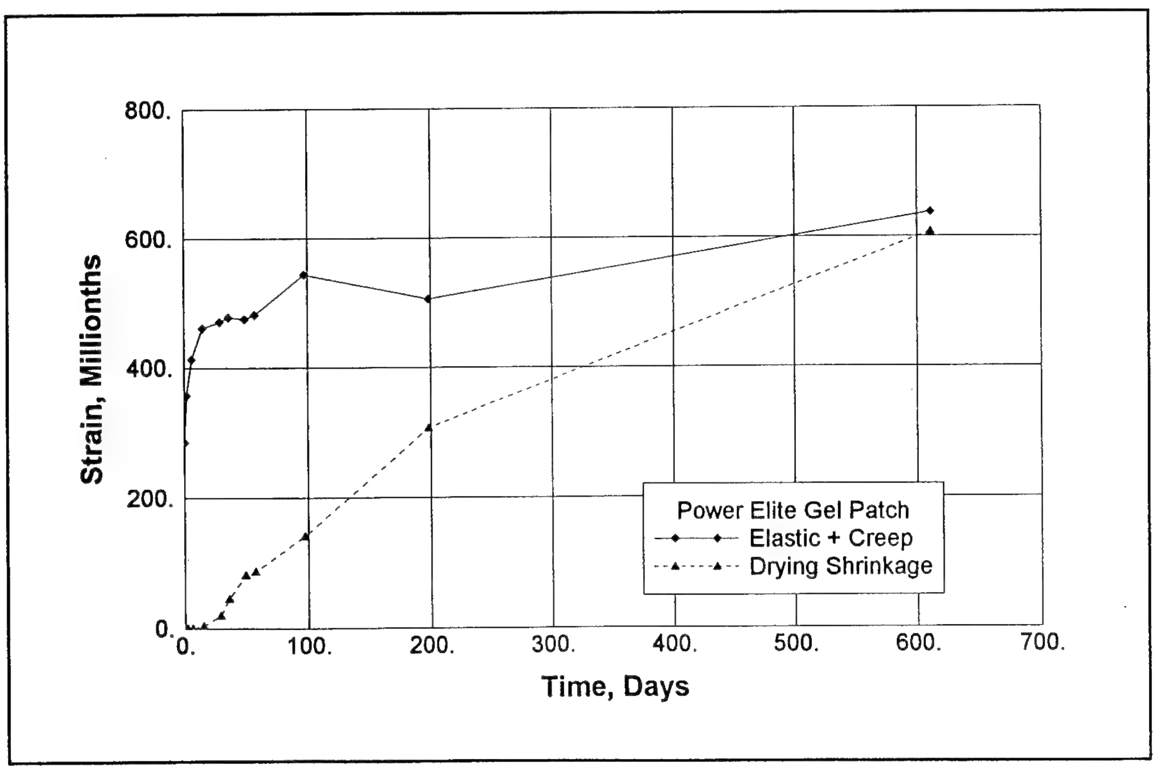

Figure 46. Results of strain measurements on creep and control specimens, material P-10

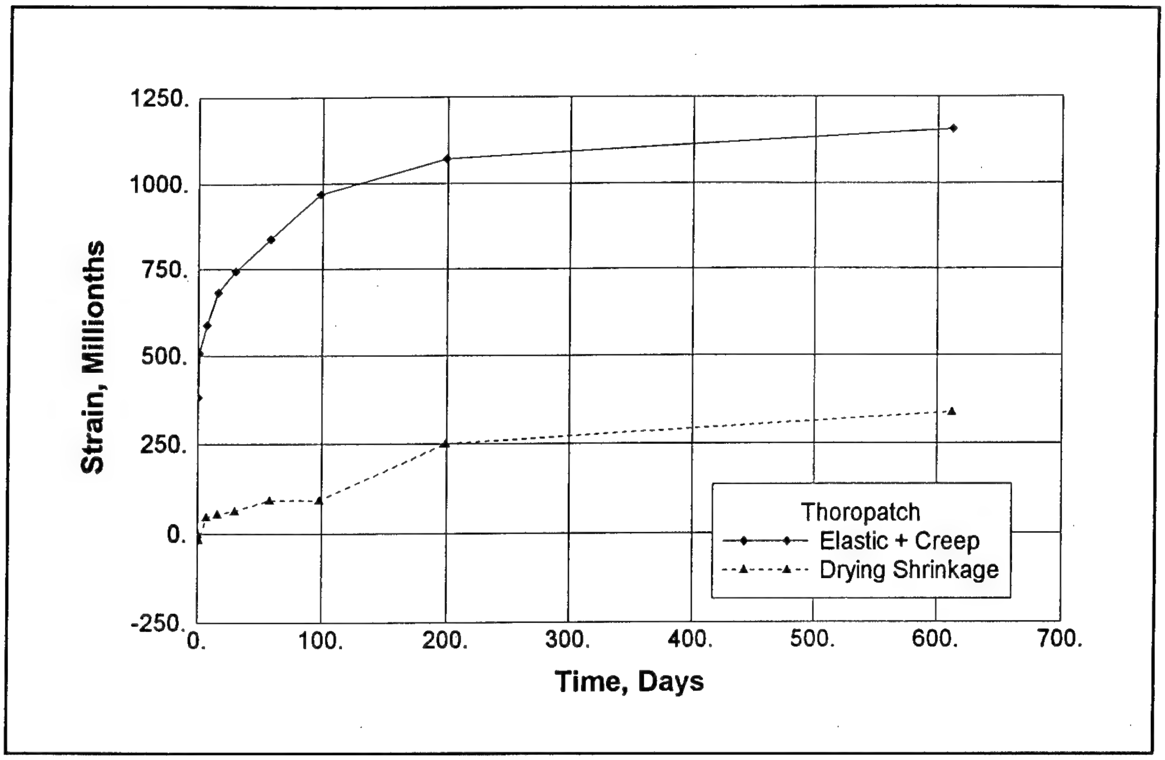

Figure 47. Results of strain measurements on creep and control specimens, material P-11

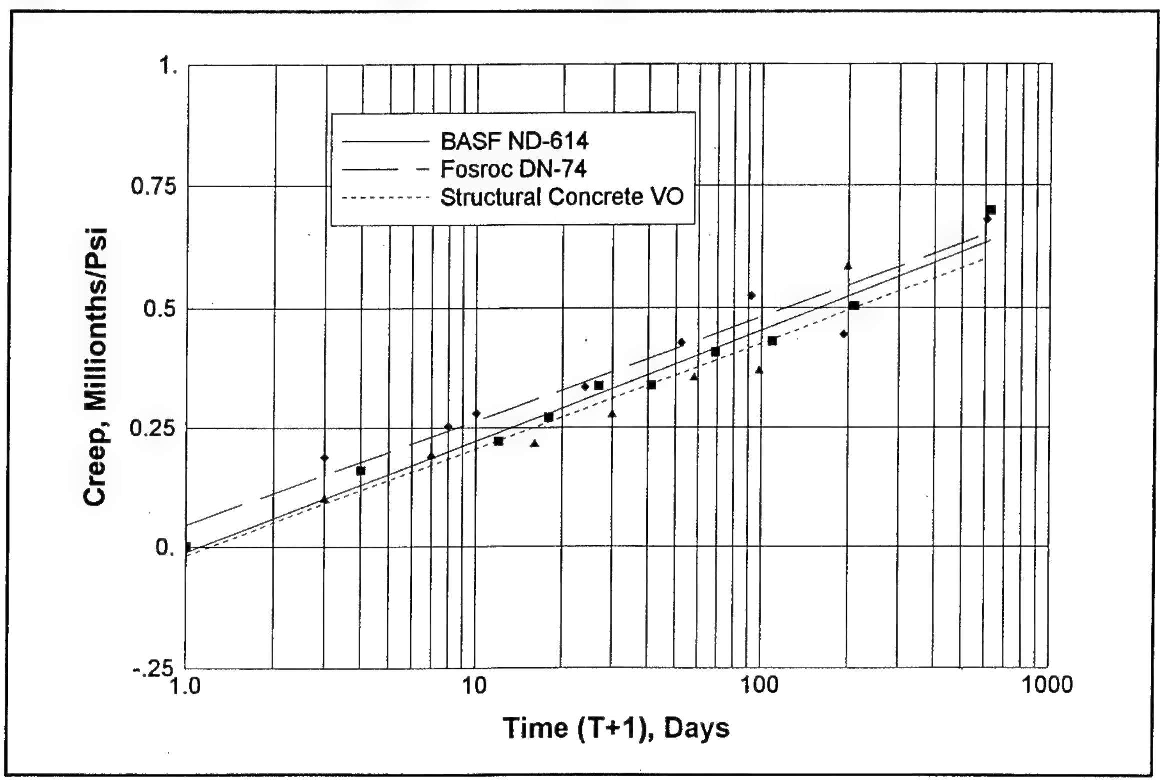

Figure 48. Specific creep strains, materials P-1, P-2, and P-3 (multiply millionths/psi by 145.0377 to obtain millionths/MPa)

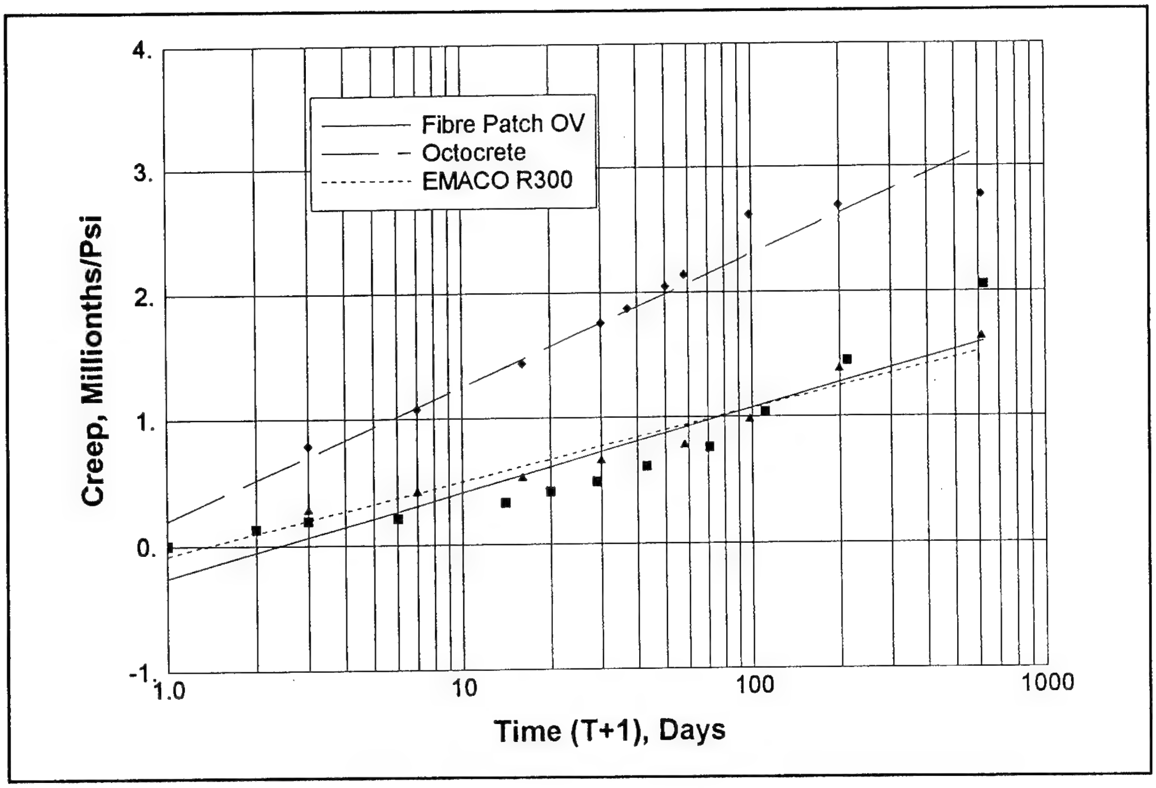

Figure 49. Specific creep strains, materials P-4, P-5, and P-6 (multiply millionths/psi by 145.0377 to obtain millionths/MPa)

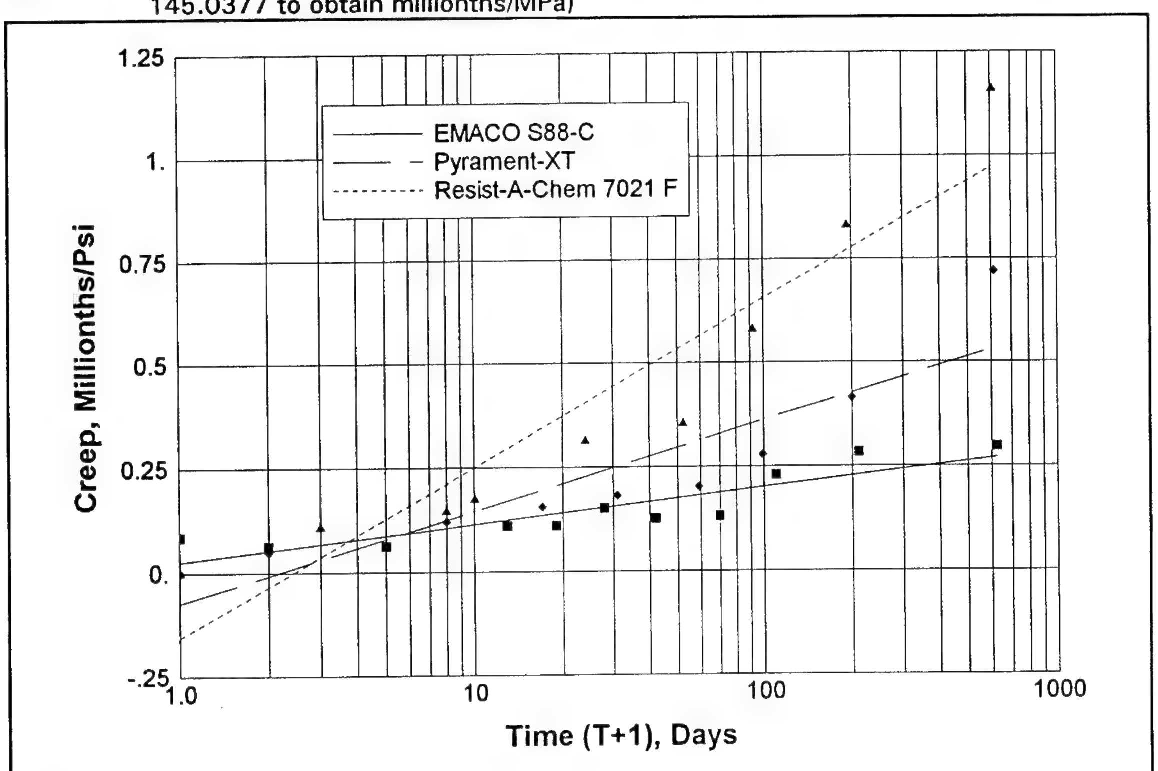

Figure 50. Specific creep strains, materials P-7, P-8, and P-9 (multiply millionths/psi by 145.0377 to obtain millionths/MPa)

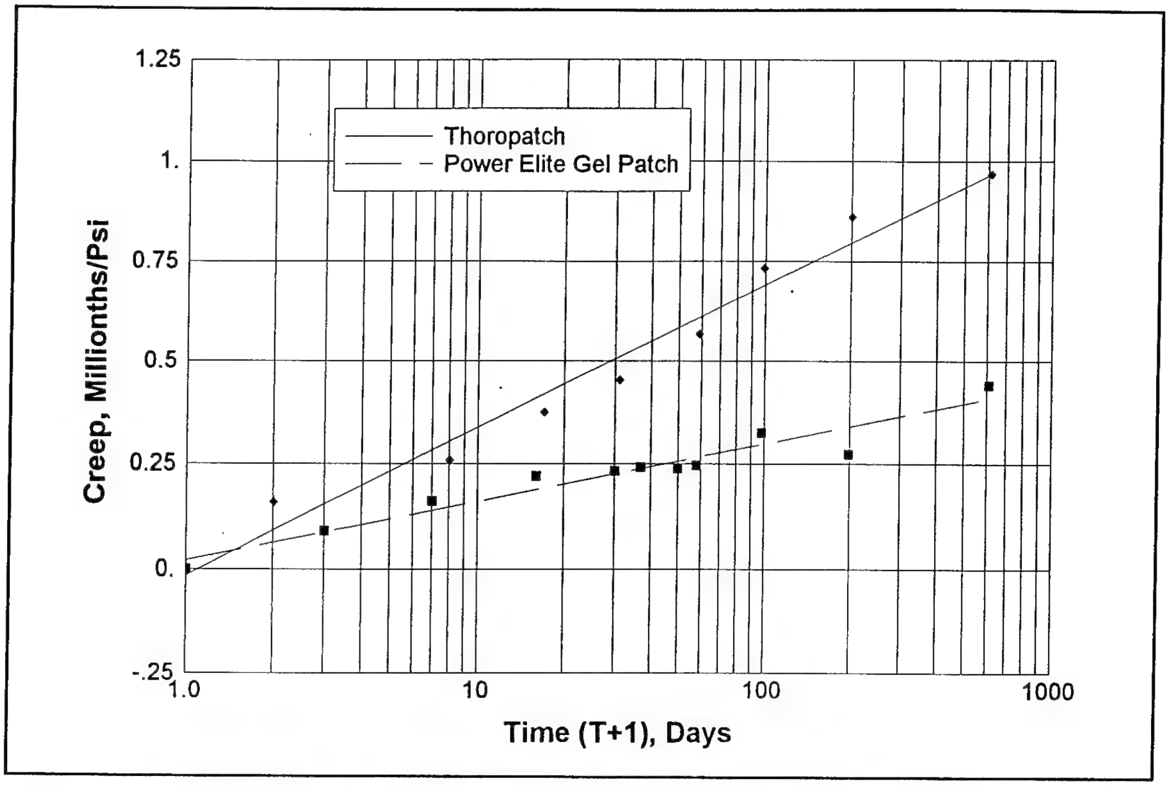

Figure 51. Specific creep strains, materials P-10 and P-11 (multiply millionths/psi by 145.0377 to obtain millionths/MPa)

Table 11
Summary of Creep Test Results

Material	Specific Creep[1] Millionths/MPa (Millionths/psi)
P-1	85.14 (0.587)
P-2	88.33 (0.609)
P-3	79.19 (0.546)
P-4	208.85 (1.440)
P-5	422.64 (2.914)
P-6	200.44 (1.382)
P-7	32.34 (0.223)
P-8	71.21 (0.491)
P-9	129.08 (0.890)
P-10	54.39 (0.375)
P-11	127.92 (0.882)

[1] Calculated creep at 1-yr age.

Table 12
Comparison of Drying Shrinkage Test Results

Material	Drying Shrinkage, Millionths		
	28 Days[1]	60 Days[1]	600 + Days[3]
P-1	470[2]		491
P-2	510		509
P-3	810		354
P-4	1,620	1,570	1,550
P-5	3,370		2,387
P-6	590	970	545
P-7	1,080	1,100	721
P-8	460[2]		416
P-9	870	900	670
P-10	1,280	1,400	607
P-11	490[2]		337

[1] 25- by 25- by 286-mm (1- by 1- by 11-1/4-in.) beams unless otherwise noted.
[2] 76- by 76- by 286-mm (3- by 3- by 11-1/4-in.) beams.
[3] 152- by 305-mm (6- by 12-in.) cylinders.

Table 13
Results of Rapid Chloride Permeability Tests

Material	Charge Passed, coulombs	Chloride Permeability[1]
P-1	1,060	Low
P-2	3,830	Moderate
P-3	280	Very Low
P-4	6,520	High
P-5	6,104	High
P-6	640	Very Low
P-7	400	Very Low
P-8	1,540	Low
P-9	1,440	Low
P-10	75	Negligible
P-11	10,050	High

[1] Based on rating guidance as follows:

Charge Passed, coulombs	Chloride Permeability
>4,000	High
2,000-4,000	Moderate
1,000-2,000	Low
100-1,000	Very Low
<100	Negligible

Table 14 Results of Water-Vapor Transmission Tests	
Material	Water-Vapor Transmission, $g/m^2/24$ hr
P-1	26.26
P-2	17.12
P-3	22.40
P-4	37.07
P-5	43.41
P-6	8.33
P-7	12.19
P-8	30.26
P-9	20.40
P-10	5.50
P-11	29.92

Restrained Shrinkage

The results of the restrained shrinkage tests are shown in Table 15. Material P-5 (Octocrete), which exhibited the highest unrestrained drying shrinkage, also exhibited the most cracks of any material tested under restrained shrinkage conditions. A test specimen prepared from material P-5 is shown in Figure 52. In contrast, no cracks were observed in four materials P-2, 6, 8, and 11 (DN-74, EMACO R300, Pyrament-XT, and Thoropatch). These four materials also exhibited the lowest values for unrestrained drying shrinkage with 28-day test results ranging from 460 to 590 millionths. A restrained shrinkage crack was observed in one specimen of material P-3 (Structural Concrete VO) which had a 28-day unrestrained shrinkage of 810 millionths. A restrained shrinkage crack was observed in both specimens of material P-9 (Resist-A Chem 7021 F) which had a 28-day shrinkage of 870 millionths. Similar performance under restraint was observed in other materials with high 28-day drying shrinkage values. In some cases, such as materials P-4 and P-7 (Fibre Patch OV and EMACO S88-C), the presence of fibers appeared to inhibit crack propagation.

Summary

The results of the laboratory tests are summarized in Table 16. Obviously, the materials evaluated exhibit a wide range of properties. Generally, it is impossible to consider a single-material property when selecting a material for a

Table 15 Results of Restrained Shrinkage Tests		
Material	**Specimen 1**	**Specimen 2**
P-2	No cracks were observed	No cracks were observed
P-3	One crack observed after 5 days in laboratory air	No cracks were observed
P-4	One crack observed after 2 days in laboratory air	One crack observed on bottom side of specimen after 6 days but did not propagate through the specimen
P-5	Six cracks observed on top side and three cracks had propagated through the specimen	Seven cracks observed on the top side and three of the cracks had propagated through the specimen
P-6	No cracks were observed	No cracks were observed
P-7	One crack observed after 4 days in laboratory air	One small crack, approximately 13 mm (½ in.) long, observed on top side after 7 days in laboratory air
P-8	No cracks were observed	No cracks were observed
P-9	One crack observed after 5 days in laboratory air	One crack observed after 6 days in laboratory air
P-10	One crack observed after 5 days in laboratory air	Two cracks observed after 5 and 6 days, respectively, in laboratory
P-11	No cracks were observed	No cracks were observed

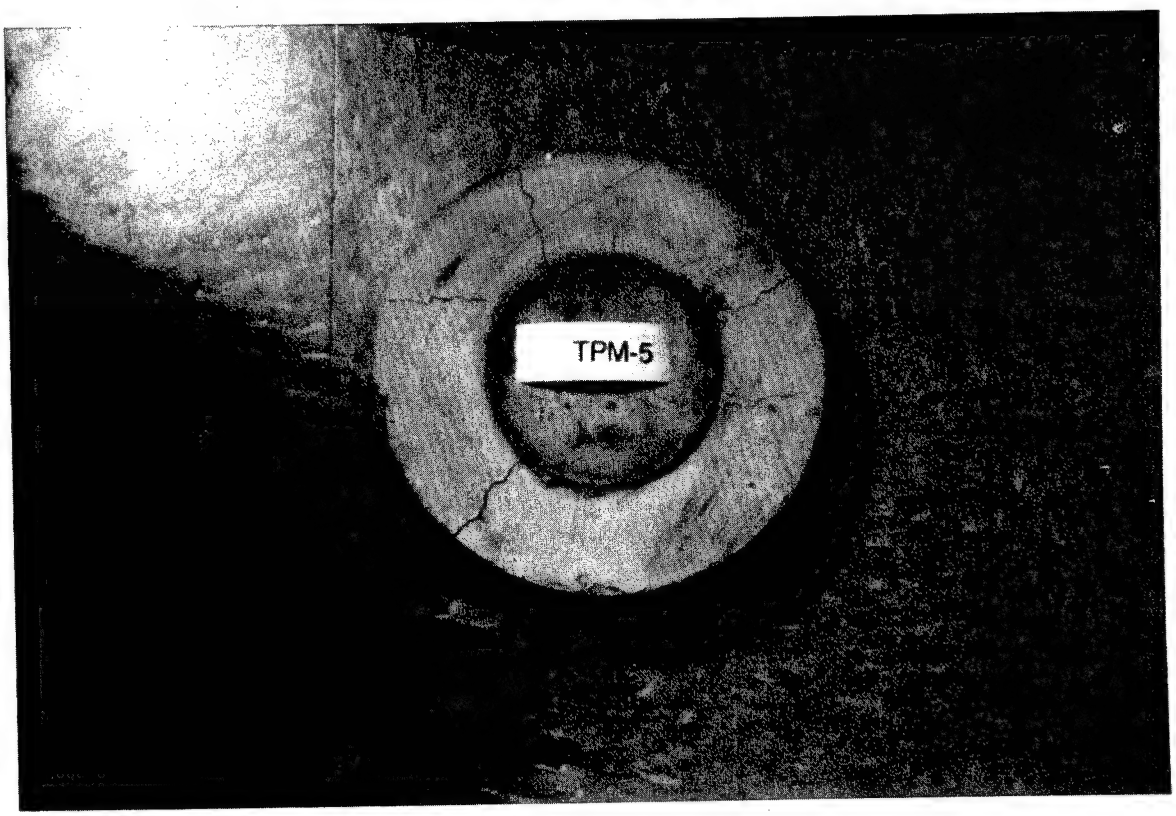

Figure 52. Results of restrained shrinkage test on material P-5

Table 16
Summary of Test Results

Material	28-day strength, MPa (psi)			Modulus, MPa x 10^4 (psi x 10^6)	Freeze-Thaw Resistance	Sulfate Expansion, %	Thermal Coefficient, Millionths/°C (Millionths/°F)	Abrasion Loss, cu m	5-hr Water Absorption, %	Curing Shrinkage, Millionths	28-day Drying Shrinkage, Millionths	Specific Creep Millionths/MPa (Millionths/psi)	Chloride Permeability	Water-Vapor Transmission, g/m²/24 hr	Restrained Shrinkage
	Compr.	Flexural	Tensile												
P-1	93.7 (6,800)	5.7 (825)	5.5 (800)	1.86 (2.70)	Good	0.000	8.75 (4.86)	0.000471	2.01	3,400	470	85.14 (0.587)	Low	26.26	--
P-2	39.4 (5,720)	5.3 (765)	2.8 (410)	1.92 (2.78)	Poor	0.014	13.10 (7.28)	0.001034	7.96	-230	510	88.33 (0.609)	Moderate	17.12	No cracks
P-3	49.8 (7,220)	8.0 (1,155)	2.9 (415)	2.43 (3.52)	Poor	0.041	9.90 (5.50)	0.000279	16.27	880	810	79.19 (0.546)	Very Low	22.40	1 crack
P-4	32.3 (4,680)	4.5 (655)	3.7 (535)	1.70 (2.47)	Poor	-0.003	10.33 (5.74)	0.001560	16.29	-90	1,620	208.85 (1,440)	High	37.07	2 cracks
P-5	44.2 (6,410)	4.7 (680)	3.0 (435)	1.17 (1.69)	Poor	0.090	11.83 (6.57)	---	3.51	320	3,370	422.64 (2.914)	High	43.41	13 cracks
P-6	46.9 (6,800)	6.2 (905)	3.0 (430)	2.48 (3.59)	Good	4.745	14.22 (7.90)	0.000623	5.63	-480	590	200.44 (1.382)	Very Low	8.33	No cracks
P-7	82.5 (11,970)	11.5 (1,675)	3.0 (440)	3.09 (4.48)	Poor	0.025	11.52 (6.40)	0.000060	7.39	-480	1,080	32.34 (0.223)	Very Low	12.19	2 cracks
P-8	65.4 (9,480)	6.3 (910)	4.0 (585)	2.50 (3.62)	Fair/Good	0.002	6.70 (3.72)	0.000123	5.37	-80	460	71.21 (0.491)	Low	30.26	No cracks
P-9	38.7 (5,610)	4.0 (585)	4.0 (575)	2.61 (3.78)	Poor	0.023	11.29 (6.27)	0.000833	13.09	490	870	129.08 (0.890)	Low	20.40	2 cracks
P-10	57.5 (8,340)	6.1 (885)	3.4 (500)	1.94 (2.82)	Poor	-0.001	12.46 (6.92)	0.000547	3.23	40	1,280	54.39 (0.375)	Negligible	5.50	3 cracks
P-11	32.5 (4,720)	4.2 (605)	2.4 (350)	1.94 (2.82)	Good	0.019	8.26 (4.59)	0.000532	13.82	580	490	127.92 (0.882)	High	29.92	No cracks

given repair. Consequently, those material properties pertinent to the application and exposure conditions of a specific repair scenario must be identified before the criteria for material selection can be established. For example, pertinent material characteristics for surface repairs in a navigation lock chamber on the upper Mississippi River might include low drying shrinkage, high abrasion resistance, freeze-thaw resistance, high water-vapor transmission, and strength properties similar to the concrete substrate. In contrast, pertinent material characteristics for protective repairs on concrete pipe in Arizona might include low drying shrinkage, thermal compatibility, low modulus of elasticity, high creep, and sulfate resistance.

The Phase II field tests represent a wide variety of environmental conditions including, high and low temperature, high and low relative humidity, and cycles of freezing and thawing. Five different geographical locations have been chosen for these exposure tests. Selected materials have been installed at the various sites and their performance will be monitored for an extended period of time.

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13. ABSTRACT *(Maximum 200 words)*

The study reported herein was Phase I of a cooperative investigation between the U.S. Army Engineer Waterways Experiment Station (WES) and the U.S. Bureau of Reclamation (USBR). The overall objective of the investigation was to identify materials appropriate for thin repair of concrete surfaces, conduct laboratory tests to determine pertinent material properties, and evaluate the perfomance of selected materials in field applications.

Eleven candidate repair materials were selected based on a review of test data, discussions with manufacturers and contractors, and examination of information that was already available at the laboratories. Each material was subjected to a suite of laboratory tests to determine pertinent material properties with results as described herein. Based on the results of these tests, selected materials have been installed at various exposure sites to evaluate their performance in field applications. The Phase II field tests represent a wide variety of environmental conditions including high and low temperature, high and low relative humidity, and cycles of freezing and thawing. Material performance will be monitored for an extended period of time.

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